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16. Abstract

This report describes the tasks of research conducted to identify effective pavement marking practices for sealcoat and hot-mix asphalt (HMAC) pavements in Texas. The researchers reviewed literature, determined current Texas Department of Transportation (TxDOT) and alternative pavement marking practices, and evaluated various pavement marking treatments in the field.

The researchers identified few shortcomings related to pavement marking practices on HMAC pavement surfaces. However, for sealcoat pavement surfaces, numerous opportunities for improving pavement marking quality were identified. Based on the research findings, numerous recommendations were developed, which pertain to thermoplastic application on sealcoat and HMAC, waterbased paint application on sealcoat, sealcoat aggregates, surface glass beads, and field inspection. The recommendations include:

- Apply thermoplastic at a *minimum* thickness of 100 mil for all longitudinal pavement markings on new sealcoat when no other durable marking exists.
- Apply thermoplastic at a *maximum* thickness of 90 mil for all longitudinal pavement markings on HMAC when no other durable marking exists.
- Waterbased paint may be used on a new sealcoat surface in either of the following situations:
  - as temporary pavement marking for up to six months, or
  - as surface primer prior to thermoplastic application.

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EFFECTIVE PAVEMENT MARKING PRACTICES FOR SEALCOAT AND HOT-MIX ASPHALT PAVEMENTS

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DISCLAIMER

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- Larry Colclasure, TxDOT Waco District;
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- Tommy Moehlman, TxDOT Bryan District;
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- Peter Eng, TxDOT Tyler District;
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- Kevin Goforth, Potters Industries;
- David Hernsberger, TxDOT Beaumont District;
- Dan Walker, TTI Operations and Design Division; and
- Michael Maresh, TTI Operations and Design Division.

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CHAPTER 1: INTRODUCTION

In September 2000, the Texas Transportation Institute (TTI) began a three-year research project sponsored by the Texas Department of Transportation to evaluate pavement markings. The goal of Project 0-4150, Evaluation of Pavement Marking Effectiveness, was to improve the performance and cost-effectiveness of pavement markings used on Texas highways. This report will focus on the performance of pavement markings on asphalt-based pavements[1], particularly pavement surface treatments (e.g., sealcoat, chipseal).

The performance of long-line pavement markings on surface treated roadway surfaces (herein referred to as sealcoat) has been a major issue for TxDOT. Sealcoated pavement surfaces are the most economical pavement surface to construct and do not require removal of the underlying roadway surface. They are, however, only designed for a seven-year service life[2]. Because of the relatively low cost per mile of sealcoat construction, the surface is commonly used for low to medium traffic volume highways in rural areas. In Texas, most rural farm-to-market highways (FM) and some rural state and U.S. highways are maintained with sealcoat surfaces. Sealcoated surfaces are uncommon in urban areas where high traffic volumes, high speeds, and high truck volumes warrant smoother and longer lasting surfaces, such as Portland cement concrete (PCC) or hot-mix asphalt concrete (HMAC).

Table 1 and Figure 1 display TxDOT centerline mileage and percentages by pavement surface type and roadway classification (*1*). Please note that sealcoat surfaces are included in the "asphalt" category.

[1] TTI research pertaining to pavement markings on Portland cement concrete surfaces has been documented in TTI report number FHWA/TX-03/4150-2, entitled *Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways*.
[2] Source: Telephone conversation with TxDOT Construction Division personnel.

Table 1. TxDOT Centerline Mileage by Roadway Class and Surface Type.

Roadway Classification	*Asphalt (Including Surface Treatments)*		*PCC*		*Total Centerline Miles*
	Centerline Miles	%	Centerline Miles	%	
Interstate	6594	85	1147	15	7741
U.S.	12,631	94	794	6	13,425
State	15,953	95	836	5	16,789
Farm-to-Market	40,777	99	218	1	40,994
TOTAL	**75,955**	**96**	**2995**	**4**	**78,950**

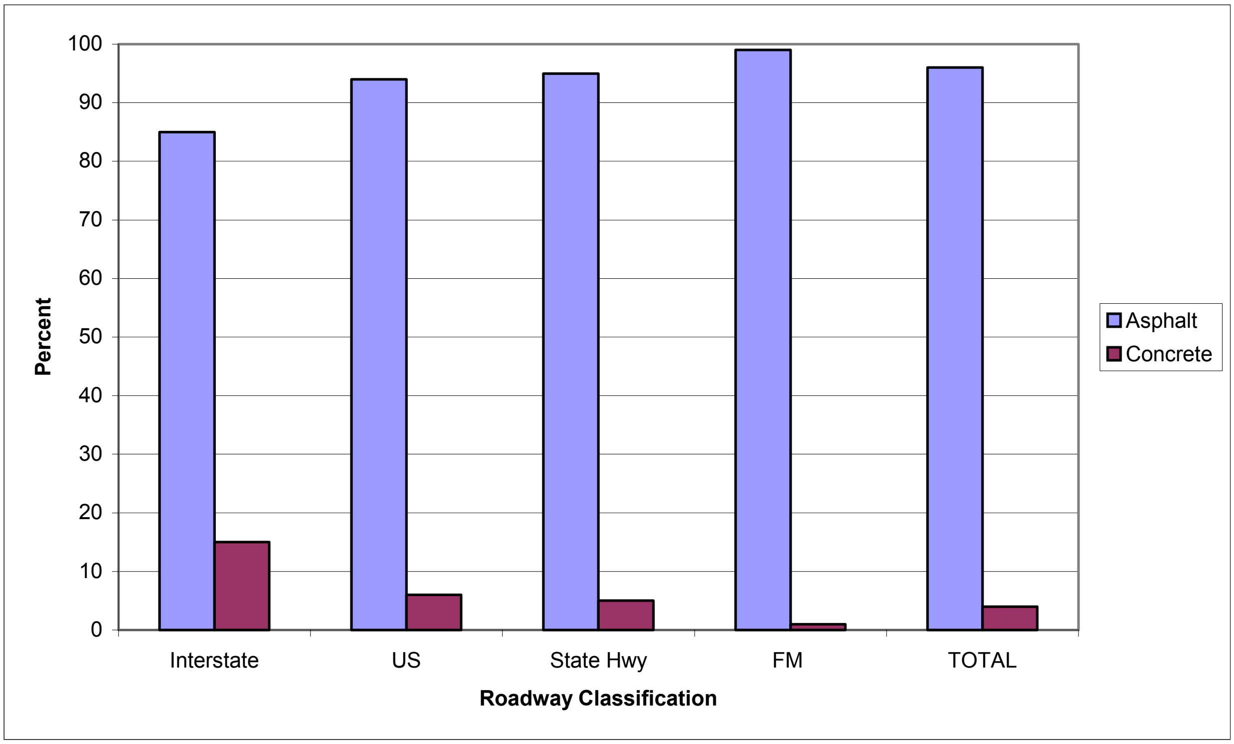


Figure 1. TxDOT Centerline Mileage for Asphalt vs. Concrete.

Asphalt pavement surfaces comprise 96 percent of TxDOT's centerline mileage, with nearly all of the mileage requiring longitudinal pavement markings. As such, pavement marking issues involving TxDOT's sealcoat and HMAC roadways are of great importance from both a safety and economic standpoint.

TEXAS THERMOPLASTIC

Thermoplastic pavement marking materials have been used in the United States since 1958, making them one of the oldest materials on the market. TxDOT has used thermoplastic pavement markings on all types of pavement surfaces for many years. Use of thermoplastic has increased over the past 10 years, likely attributed to recent TxDOT initiatives calling for a reduction in the use of paint and ceramic buttons. Consequently, most of the longitudinal pavement markings on TxDOT roadways are thermoplastic.

Thermoplastic pavement markings are the most heavily used pavement marking materials in Texas for a number of reasons, including:

- material availability,
- contractor availability,
- reasonable cost, and
- good performance.

Thermoplastic pavement marking materials generally show superior performance on HMAC roadways, although issues have been raised with the durability of thermoplastic pavement markings on both sealcoat and concrete surfaces in Texas.

TxDOT classifies thermoplastic materials as a Type I pavement marking material. TxDOT currently uses a "recipe" alkyd thermoplastic specification (DMS 8220) for standard sprayed thermoplastic applications. Although other thermoplastic formulations and application processes are allowed and are sometimes used by TxDOT districts through special provision or specification, sprayed TxDOT alkyd thermoplastics are used most often. Table 2 shows the characteristics of TxDOT alkyd thermoplastic for sealcoat application.

Table 2. Characteristics of TxDOT Alkyd Thermoplastic for Sealcoat Application.

Initial Contracted Material Cost ($/lft)	Total Life Cycle Cost ($/lft)	Typical Service Life (years)	Total Cost per Year of Service Life ($/lft/yr)	Surface Preparation	Minimum Thickness on New Sealcoat (mil)	No-Track Time (sec)	Lane Closure Reqd.?
0.20	0.30	2 - 3	0.10 - 0.15	Remove: dirt, loose aggregate, loose marking materials	100	30	No

Note: lft = linear foot

PROBLEM STATEMENT

Pavement markings on sealcoated roadways have been an important issue for TxDOT, and as a result were a major focus of the research described in this report. Over the past decade, most TxDOT districts have experienced various problems with the retroreflectivity and durability of pavement marking materials on newly sealcoated roadway surfaces. A major issue is that longline thermoplastic pavement markings placed on newly sealcoated roadways often do not maintain suitable levels of retroreflectivity throughout their intended service lives. Multiple in-service retroreflectivity investigations for thermoplastic on various sealcoats support this claim.

OBJECTIVE AND TASKS

The focus of the research performed and described herein involved identification of the problems with pavement markings on new sealcoats and HMAC surfaces, causes of these problems, and determination of feasible solutions. Early in this project, it became evident to TTI researchers that a majority of the research effort would focus solely on sealcoat pavement marking issues, which is therefore reflected in this report.

Prior to the start of this research project, most pavement marking evaluations performed in Texas were purely subjective, with little scientific evaluation. TTI researchers conducted several tasks to help TxDOT identify the pavement marking material applications that are best suited for sealcoated and HMAC roadways. These tasks are listed below and are described in more detail in the following section:

- Review the available literature.
- Survey TxDOT districts to determine common pavement marking issues and practices.
- Identify performance of in-service pavement markings.
- Facilitate open-dialogue meetings between TxDOT staff, contractors, and industry personnel to identify issues and corresponding solutions related to pavement markings in Texas.
- Perform field evaluations of various pavement marking applications on sealcoat and HMAC pavements.
- Develop service life estimations for thermoplastic applications on sealcoat, HMAC, and PCC roadways.

This report details the findings resulting from the major tasks. The first four tasks in the preceding list were important for identification of the pavement marking treatments evaluated in the field and are detailed in Chapters 2 and 3. The final tasks in the list comprised a majority of the data collection and analyses performed in this project and are described in Chapters 4 and 5. Conclusions and recommendations for pavement markings on sealcoated and HMAC pavements in Texas are made in Chapter 6.

CHAPTER 2:
LITERATURE REVIEW

Researchers performed a review of the literature to identify previous research pertaining to relevant delineation-related issues, including:

- driver visibility needs,
- pavement marking retroreflectivity,
- recommendations for minimum levels of pavement marking retroreflectivity, and
- performance of various pavement marking materials.

The literature review included reports sponsored and/or published by state and federal transportation agencies. The researchers were particularly interested in research performed within the last decade, as pavement marking materials are modified frequently.

VISIBILITY NEEDS OF DRIVERS

Prior to analyzing the performance of various pavement marking applications in the field, it was necessary to first establish the delineation needs of drivers. In a general sense, the ability of a driver to safely operate a vehicle is based on the driver's perception of a situation, level of alertness, the amount of information available, and the driver's information assimilation capabilities (*2*). Although the transportation profession can do little to control a driver's level of alertness or information-processing capabilities, necessary roadway information can be communicated through traffic control devices, including pavement markings. Pavement markings are critical for roadway navigation because they provide a simple, continuous stream of roadway information to the driver's central vision. To be effective, pavement markings must (*2*):

- present the appropriate visual clues far enough in advance of a given situation to allow for suitable reaction time to occur, and
- be visible in the periphery to aid in moment-to-moment lane navigation.

This is especially true at night when the visibility of the roadway and surrounding features drops dramatically, causing motorists to rely heavily on pavement marking visibility for delineation cues.

Minimum Necessary Driver Preview Time

The nighttime preview time (or distance) provided by a pavement marking is the most commonly used method of quantifying the visibility performance of pavement markings. For pavement markings to be effective, the preview distance that they provide must be large enough to allow most drivers sufficient time to perform all of the necessary delineation-related tasks including (*2*):

- detect change in delineation,
- recognize message being conveyed,
- decide appropriate reaction,
- initiate response, and
- complete vehicle maneuver.

Research has suggested that as a minimum, 3 to 3.65 seconds of delineation preview is necessary to complete these tasks and allow for some margin of driver error and driver comfort. As a result, researchers have recommended that delineation devices provide a minimum of 3 to 3.65 seconds of preview time for long-range guidance under normal driving conditions (*2,3*).

PAVEMENT MARKING VISIBILITY

The ability to actually see a pavement marking at night depends on many factors, including:

- intensity of the light source,
- amount of light actually striking the pavement marking,
- retroreflective characteristics of the pavement marking, and
- visual characteristics of the driver.

Not all drivers require the same amount of light from pavement markings to safely navigate. For example, older drivers or drivers with visual impairments often need more light to see the same distance as a younger or non-impaired driver. Cognitive capabilities, which include attention and information processing, are known to decline with age. Cognitive declines often result in drivers having longer reaction times and increased driver workload. Declines in motor skills increase the amount of time needed to react to stimuli and perform a driving maneuver.

Similarly, roadway characteristics influence the amount of light needed. The speed of the vehicle influences the amount of light needed because at higher speeds, a greater distance is needed to make a maneuver, thereby requiring earlier detection. Roadway lighting and retroreflective raised pavement markers both aid in the navigation tasks and reduce the amount of light needed from the pavement markings for safe navigation.

A number of environmental factors can also reduce the visibility of pavement markings, including inclement weather, moisture on the marking surface, surface glare, and fog. Considering all factors that influence marking visibility, retroreflectivity is the only factor that transportation agencies can realistically control.

PAVEMENT MARKING RETROREFLECTIVITY

Pavement markings are designed to reflect a portion of the headlamp illumination back to the driver's eyes. This phenomenon is referred to as retroreflection. Both the Texas and Federal Manuals on Uniform Traffic Control Devices (MUTCD) require that all pavement markings be retroreflective if they are to be visible at night, unless ambient illumination assures that the markings are adequately visible (*4*,*5*). In addition, both manuals state that all markings on Interstate highways shall be retroreflective.

Properties

Retroreflection in pavement markings is provided through the use of glass beads embedded into the surface of the marking. Without the glass beads providing retroreflection, a much larger proportion of the light striking the marking would be diffused in all directions. The effectiveness of the glass beads as retroreflectors depends on:

- depth of bead embedment,
- bead dispersion,
- refractive index of the beads, and
- reflective characteristics of the binder material.

Figure 2 illustrates how retroreflection occurs within a pavement marking structure.

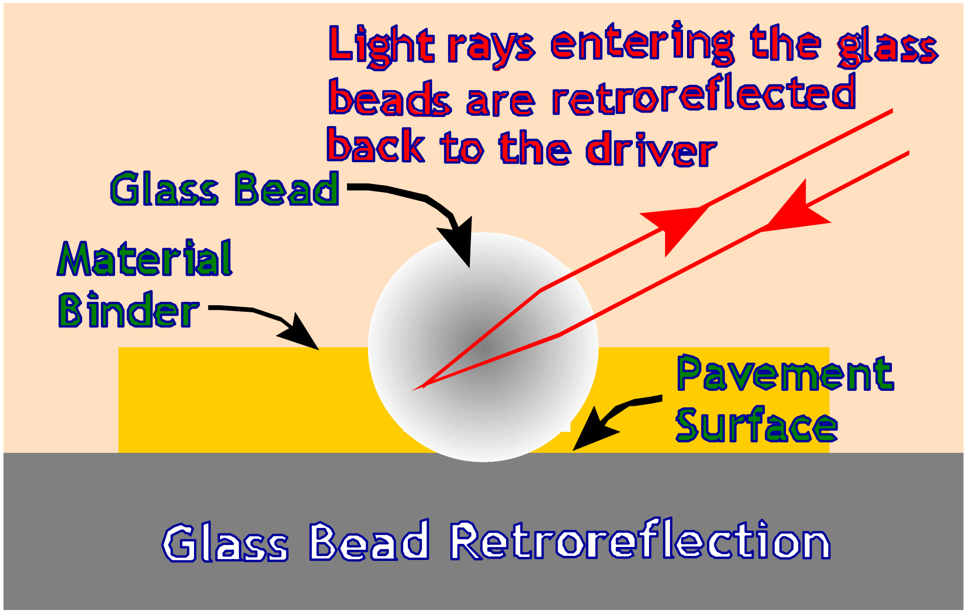


Figure 2. Glass Bead Retroreflection.

Retroreflectivity Measurement

Measuring the retroreflectivity of pavement markings is one of the most widely used methods to objectively evaluate nighttime performance of pavement marking. In general, the more retroreflective the markings, the more visible they are at night.

A number of commercially available portable handheld retroreflectometers exist and are used extensively by transportation agencies. Mobile retroreflectometers are also available, although contractors perform most mobile retroreflectivity measurement for state departments of transportation (DOTs). Whether taken with a handheld instrument or mobile unit, retroreflectivity measurement provides a reasonably good indication of nighttime brightness of the pavement markings under headlamp illumination.

Standard Measurement Geometry

Pavement marking retroreflectivity is defined as the ratio of the retroreflected luminance to the perpendicular headlamp illuminance and is denoted by the symbol R_L with units of $mcd/m^2/lx$. The magnitude of R_L is dependent on the entering illumination geometry and the observation geometry. For standardization purposes, the American Society of Testing and Materials (ASTM) and the European Committee on Standardization (CEN) have adopted the entry and observation angles corresponding to a 30-meter viewing geometry, which simulates the performance of a marking that is located 30 meters (98.4 feet) in front of the vehicle[3]. Most common handheld and mobile retroreflectometers simulate this measurement geometry. All retroreflectivity data collected and reported herein were measured with a 30-meter handheld retroreflectometer.

Human Factors Research

Numerous research evaluations have investigated the relationship between nighttime driver visibility needs and the retroreflectivity of pavement markings. While there is a definite correlation between pavement marking retroreflectivity and the visibility of the markings, the major issue that each research study has attempted to address is: "How bright is bright enough?" The findings from many existing literature sources suggest that this issue is difficult to resolve, as a wide variety of minimum pavement marking retroreflectivity values have been suggested. The literature search uncovered two main types of retroreflectivity-based human factors evaluations:

- subjective evaluations and
- detection distance evaluations.

Subjective evaluations generally involved subjects driving or being driven through various sections of highway at night and rating the quality of the pavement markings in each section. The subjective evaluations found in the literature have produced recommended minimum retroreflectivity values ranging from approximately 80 to 120 mcd/m^2/lx (*6*,*7*,*8*). One criticism of subjective evaluations is that they do not necessarily correlate to the preview distances provided by the marking in question (*9*). In other words, drivers do not necessarily know the amount of pavement marking brightness actually needed for safe navigation.

Detection distance evaluations involve subjects driving or being driven through multiple sections of pavement markings, each with prescribed levels of retroreflectivity. The subjects call out when they are able to first detect the beginning or end of a given section of marking. The resulting detection distances and corresponding retroreflectivity levels are then compared to the minimum necessary detection distances, which are based on the operating speed and minimum necessary preview time (generally accepted as 3 to 3.65 seconds). Detection distance data have also been used in the development and calibration of various pavement marking visibility

[3] See ASTM E1710-97 and ASTM D6359-98.

models. Based on detection distance field studies and modeling efforts, the range of acceptable levels of pavement marking retroreflectivity is approximately 400 to 515 mcd/m^2/lx for older drivers traveling at 70 mph on dark highways without retroreflective raised pavement markings RRPMs (*10*,*11*). Research has also shown that a fully marked road consisting of both edge lines and centerlines of similar retroreflectivity, on the average provides end detection distances that are about twice as long as the end detection distances that can be achieved with a centerline alone (*12*). This finding suggests that end detection distances on a fully marked road are governed by the visibility of the edge lines, thereby supporting their use for roadway visibility enhancement.

It is also widely recognized that older drivers require higher quality pavement markings than do younger drivers. Zwahlen and Schnell found that on a fully marked high-speed roadway, a 62 year old driver requires approximately twice the retroreflectivity as a 22 year old in order to have the same detection distances (*10*). Similarly, younger drivers have been shown to possess detection distances that are on average 55 percent longer than older drivers (*11*). Additionally, it also appears that pavement marking visibility for older drivers is affected more by the visual angle of the markings than by the brightness, suggesting that wider markings may be more detectible by the elderly.

Minimum In-Service Retroreflectivity Guidelines

Although both the Texas and Federal MUTCDs require that all pavement markings be retroreflective if they are to be visible at night (*4,5*), no numerical values are currently associated with this requirement. FHWA is currently developing minimum retroreflectivity standards, as directed by the United States Congress.

As a result of the Congressional directive, FHWA has developed draft recommendations for minimum retroreflectivity values for various roadway scenarios. These draft recommendations are largely based on the previously mentioned research studies. FHWA-recommended retroreflectivity levels for high-speed roadways without RRPMs or continuous roadway lighting are 150 mcd/m^2/lx for white and 100 mcd/m^2/lx for yellow (*13*). Where additional roadway visibility is provided at night by retroreflective raised pavement markings or continuous roadway lighting, lower retroreflectivity levels may be acceptable. These draft recommendations currently do not constitute a standard and exist for purposes of providing guidance to agency personnel. It is not yet known when nationwide compliance with federal minimum retroreflectivity standards will go into effect, although many state transportation agencies have already begun monitoring the retroreflectivity of their pavement markings. Extensive European research has resulted in a similar recommended minimum in-service retroreflectivity level of 100 mcd/m^2/lx (*14*).

PAVEMENT MARKING PERFORMANCE

Many materials are available for use as pavement markings. However, the service life and cost of materials vary greatly. As with other traffic control devices, maintaining pavement markings that are highly visible and long lasting presents a major challenge to transportation agencies.

In general, pavement marking performance is judged by two criteria: durability and visibility (*2*):

- ***Durability*** refers to the amount of material remaining on the pavement surface over time. Durability performance is often measured either by determining the percentage of material remaining on the surface or by directly testing the bond strength of a material to the surface.
- ***Visibility*** relates to the brightness of the material. Much of the research concerning marking visibility uses retroreflectivity as a proxy measure for visibility performance.

It is important to recognize that most pavement marking materials do not provide equal durability and visibility under every roadway situation. Performance for a specific material may vary widely based on many factors, including roadway surface type, traffic volume, and environment/weather. Each of these factors must be considered when selecting the optimum pavement marking material for a given set of roadway, traffic, and environmental circumstances.

Sealcoated Pavement Surface Characteristics

Prior to addressing the problems associated with pavement markings on sealcoated pavement surfaces, one must first address the issues involving the sealcoats themselves. Sealcoated surfaces are classified as an improved pavement surface, although are generally considered as a lower quality surface when compared to hot-mix asphalt concrete or Portland cement concrete surfaces due to the lower structural capacity and rougher ride quality that sealcoats provide. Sealcoated surfaces usually have a higher degree of surface texture and variability when compared to other types of pavement surfaces.

The greater surface variability can be attributed to sealcoats being field-constructed rather than premixed like HMAC or PCC surfaces. The coarser surface texture is a result of the aggregates being dropped on to the asphalt binder material rather than intermixed like an HMAC or PCC surface. The lack of intermixing of sealcoat materials creates much larger surface voids on the sealcoat than are observed with the riding surfaces of HMAC and PCC pavements. Although the fresh sealcoat surface is rolled during construction, traffic loads are relied upon to further embed the aggregates into the binder as it cures. This process leads to a much higher likelihood of aggregates "popping out" of a fresh sealcoat surface than the premixed surfaces, although pop-outs tend to decrease as the sealcoat surface cures. Fresh sealcoats are also susceptible to bleeding and tracking of the asphalt binder material across the pavement surface and onto the markings.

Expected Service Life of Thermoplastic Pavement Markings

The service life of a pavement marking can be defined as the time or number of traffic passages required for its retroreflectivity to decrease from its initial value to a minimum threshold value that indicates that the marking needs to be refurbished or replaced (*15*). The literature has shown that determining an expected service life (or design life) for thermoplastic pavement markings is not necessarily an easy task due to the sensitivity and variability of thermoplastic materials.

A comprehensive study by Migletz, et al. explored the service lives of a variety of durable pavement markings (*15*). Various durable pavement markings were placed in 19 states at 85 study sites, and the retroreflectivity of the markings was monitored approximately every six months for nearly four years. Expected service lives were predicted by modeling the retroreflectivity data as a function of time or cumulative traffic passages. End-of-service life thresholds were set at the FHWA recommended minimums (*13*). This study found large site-to-site variations in the retroreflectivity data for identical materials and line types. Because of these variations, the modeling was performed separately for each individual pavement marking line at each study site. The large site-to-site variability in the retroreflectivity data for identical materials and line types suggests that the retroreflectivity of marking materials is affected by a number of roadway, weather, and application related variables that are difficult to quantify. However, the study did find that both white and yellow thermoplastic pavement markings could be expected to last two years on freeways and three years on non-freeways when the FHWA recommended threshold retroreflectivity levels were used. The study found maximum service life for thermoplastic to be approximately four years. Unfortunately, no mention was made pertaining to the pavement surfaces included in the evaluations, which may also help to explain the site-to-site variability.

TxDOT district and division personnel have indicated that an expected service life of two to three years is reasonable for thermoplastic markings placed on new sealcoat surfaces. Therefore, based on the findings of Migletz, et al. (*15*) and observations by TxDOT personnel, an expected service life of two to three years with a maximum of four years is reasonable for thermoplastic pavement markings placed on TxDOT sealcoat roadways.

LITERATURE SUMMARY

The literature review provided important information pertaining to pavement markings, which aided the researchers in other research tasks. The following information was obtained from the literature:

- To be effective, pavement markings must:
  - present the appropriate visual clues far enough in advance of a given situation to allow for suitable reaction time to occur, and
  - be visible in the periphery to aid in moment-to-moment lane navigation.
- Providing 3 to 3.65 seconds of delineation preview gives drivers sufficient time to complete standard driving tasks and allows for some margin of driver error and driver comfort.
- Measuring the retroreflectivity of pavement markings is one of the most widely used methods to objectively evaluate nighttime performance of pavement markings.
- For standardization of pavement marking retroreflectivity measurement, ASTM and CEN have adopted the entry and observation angles corresponding to a 30-meter viewing geometry.

- Most drivers will classify pavement markings with minimum retroreflectivity values ranging from approximately 80 to 120 mcd/m^2/lx to be acceptable.
- The FHWA-recommended retroreflectivity levels for high-speed roadways without RRPMs or continuous roadway lighting are 150 mcd/m^2/lx for white and 100 mcd/m^2/lx for yellow.
- Thermoplastic pavement markings are expected to last two years on freeways and three years on non-freeways, with a maximum of four years.

CHAPTER 3: IDENTIFICATION OF MAJOR ISSUES

Prior to conducting comprehensive pavement marking field evaluations, TTI researchers first identified many of the major problems, issues, and challenges involved with pavement markings on sealcoats on TxDOT roadways. Identification of these items was accomplished through a series of tasks that included:

- surveying TxDOT districts,
- performing preliminary field studies of in-service marking performance, and
- facilitating two major pavement marking conferences for pavement marking stakeholders in Texas.

SURVEY OF TXDOT DISTRICTS

One of the first project tasks was to determine the sealcoat pavement marking practices of TxDOT's 25 districts. To accomplish this task, the research team developed a survey and sent it electronically to traffic and maintenance personnel within each district in December 2000. The survey focused on determining types of pavement marking materials used, thickness of markings, required cure time for sealcoats prior to applying markings, use of retroreflectivity performance specifications, grade of sealcoat aggregate, etc. Appendix A contains the survey questionnaire form. The responses to the survey were useful for:

- gaining knowledge of the current statewide pavement marking practices on new sealcoats,
- identifying major issues and challenges with pavement markings on sealcoats, and
- developing field evaluations of various pavement marking treatments.

Survey Results

Responses were received from 22 of the 25 TxDOT districts. Responses represent TxDOT district practices during late 2000/early 2001. The survey results are summarized in Figures 3-6.

Question: What type of marking material do you currently install on a new sealcoat?

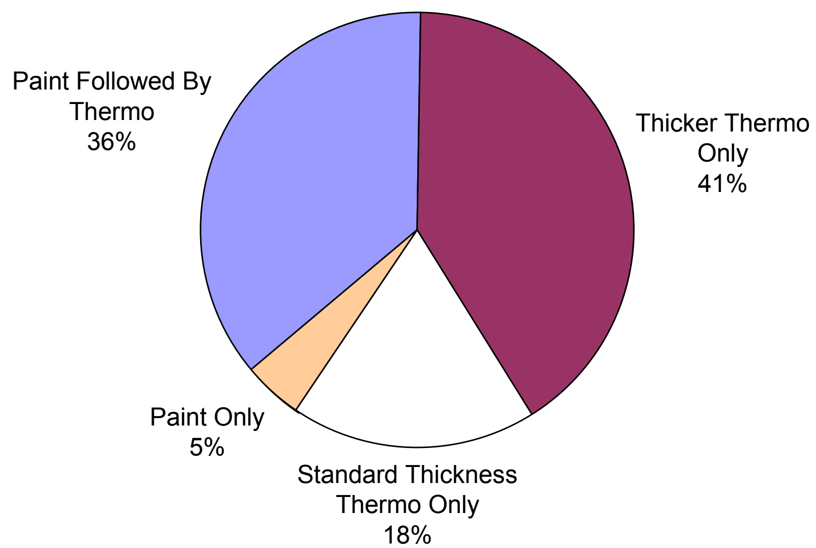


Figure 3. Pavement Marking Materials on New Sealcoat.

Question: If you initially apply waterbased paint on a new sealcoat, how long do you wait before applying thermoplastic?

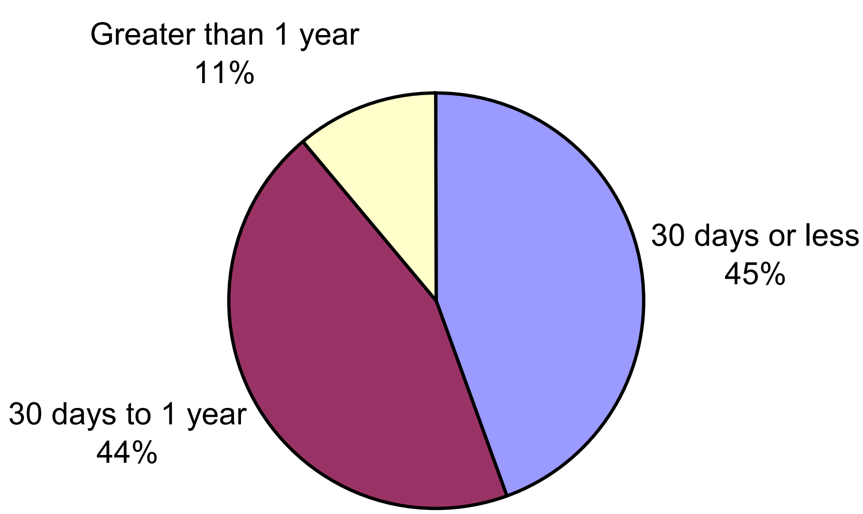
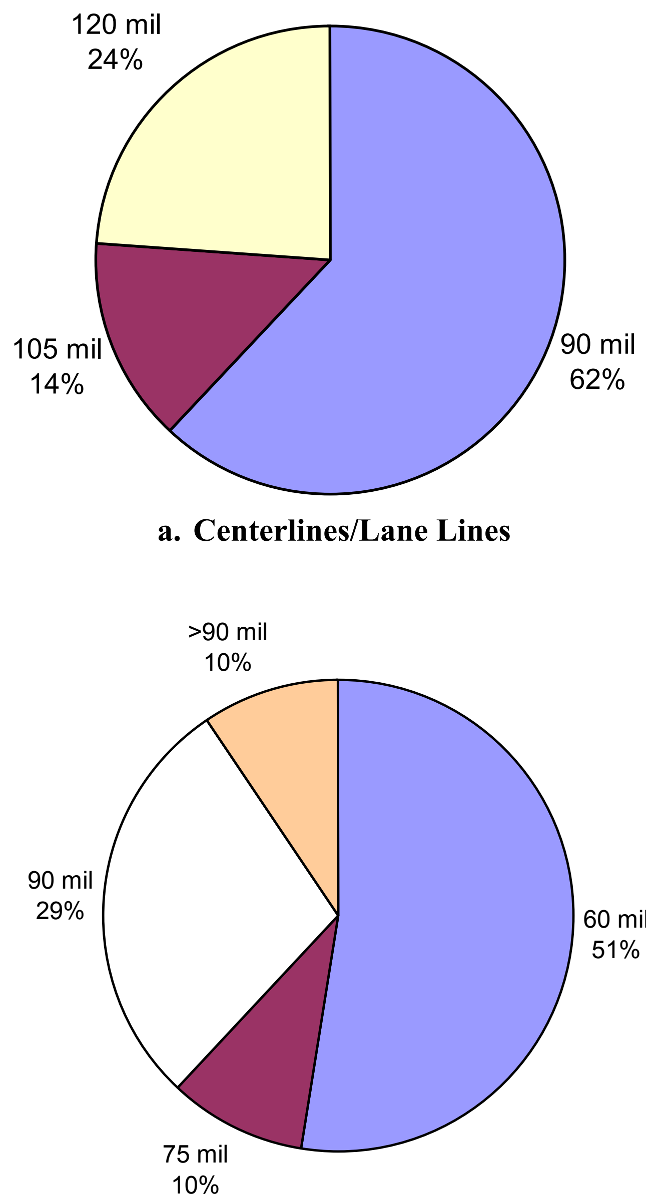


Figure 4. Waiting Time between Waterbased Paint and Thermoplastic.

Question: If you apply thermoplastic on a new sealcoat, what thickness is typically applied?



a. Centerlines/Lane Lines

b. Edge Lines

Figure 5. Thermoplastic Thickness on New Sealcoat.

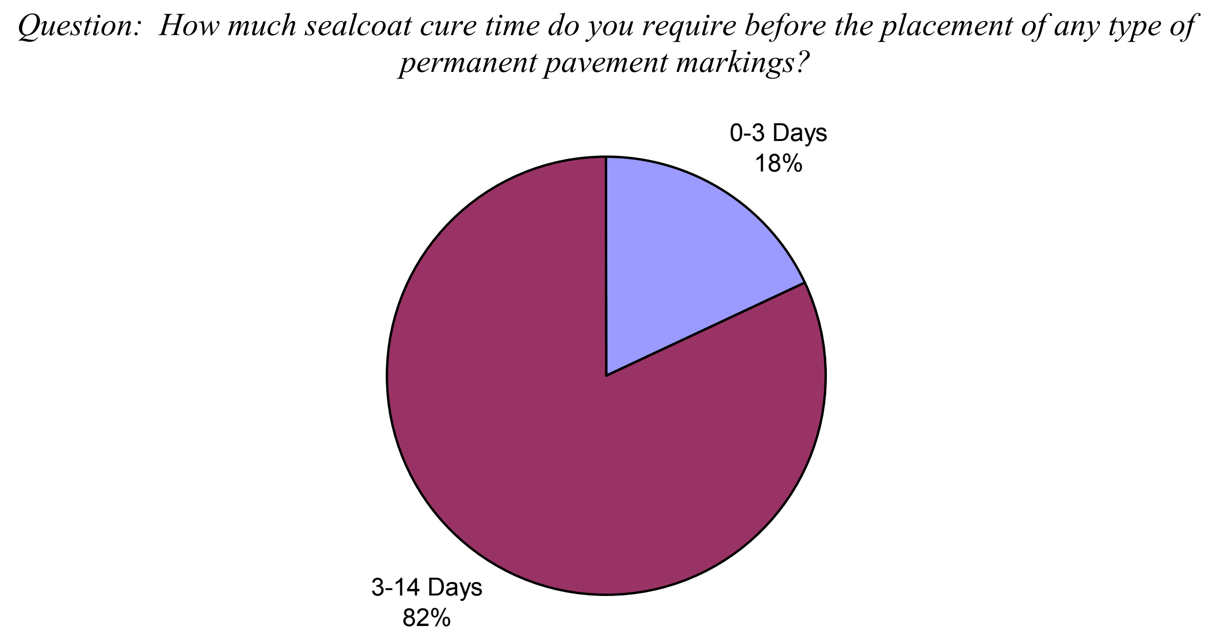


Figure 6. Time between Sealcoat Placement and Permanent Striping.

One of the more useful portions of the survey was respondent lists of problems experienced with markings on new sealcoats. The following is a sample of the responses:

- rapid deterioration of retroreflectivity for thermoplastic,
- paint often does not last a full year when placed on a new sealcoat,
- unable to cover the entire aggregate surface with thermoplastic sprayed at standard thickness,
- thermoplastic on tops of the aggregates wears quickly,
- asphalt bleeding to surface and tracked onto new markings,
- aggregates "pop out" of the new sealcoat surface and remove the marking material,
- contractors have difficulty spraying thermoplastic greater than 90 mils, and
- contractors have difficulty applying thermoplastic within the 14-day requirement after sealcoat is placed.

PRELIMINARY PAVEMENT MARKING INVESTIGATIONS

The first data collection activities involved field investigation of pavement marking conditions to determine the current state of pavement markings on TxDOT's sealcoated highways. These field investigations included taking retroreflectivity measurements and making observations as to the condition of the markings.

In-service investigations for thermoplastic pavement markings were performed on a number of TxDOT highways from December 2000 through January 2001. Each of these roadways had been sealcoated (TxDOT Grade 4) in early summer 2000 and striped with thermoplastic within one week after surfacing. The same contractor performed all striping work. Average annual daily traffic volumes ranged from approximately 500 to 4500 vehicles.

Retroreflectivity measurements were made with a hand operated 30-meter instrument and were taken from mid-December through early January, at which time the markings had been in place between 6.5 and 7 months for all roadways. Unfortunately, the initial retroreflectivity of the markings was not measured and therefore remains unknown. Figure 7 shows the average in-service retroreflectivity for white and yellow thermoplastic markings on sealcoat.

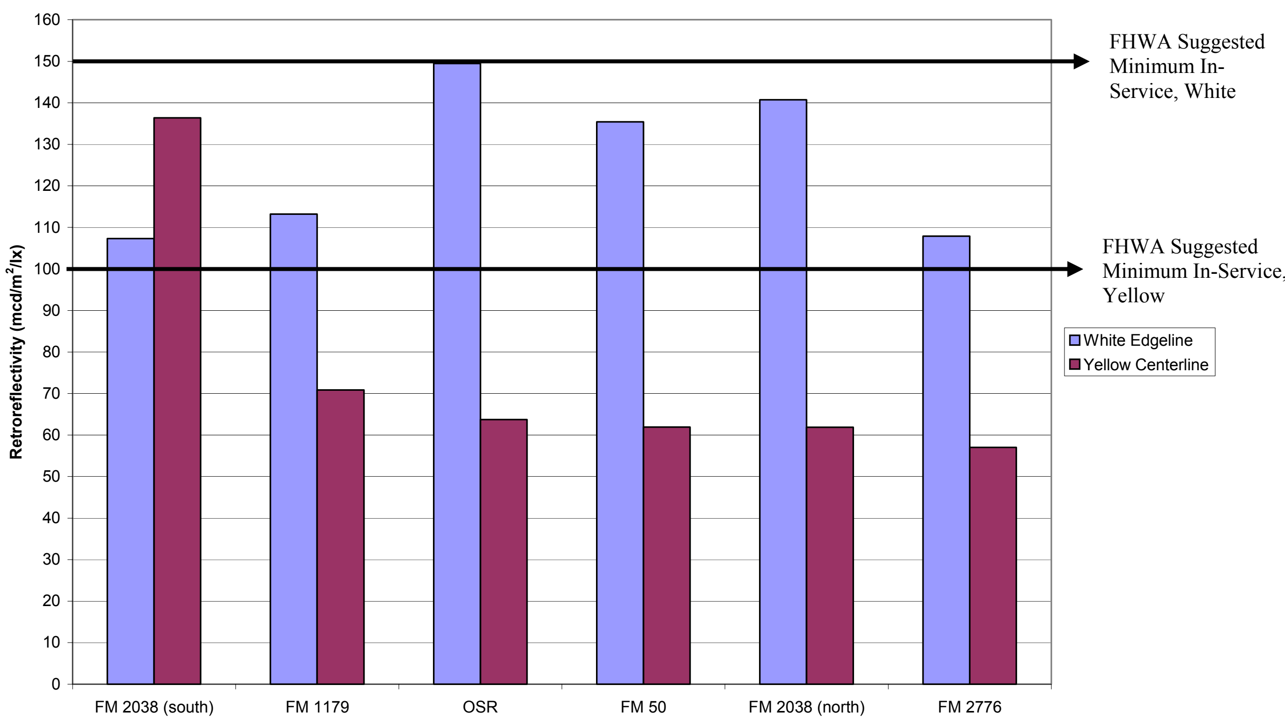


Figure 7. In-Service Retroreflectivity Averages for Thermoplastic Markings on Sealcoat.

Figure 7 shows that although the pavement markings had only been in place for approximately 7 months, all but one of the averages are below the FHWA proposed minimum in-service retroreflectivity recommendations of 150 and 100 mcd/m^2/lx for white and yellow markings, respectively (*13*). These data provide objective evidence supporting TxDOT's belief that thermoplastic markings on new sealcoats often do not provide sufficient retroreflectivity throughout their expected service lives of two to three years.

PAVEMENT MARKING CONFERENCES

Shortly after this research project began in September 2000, TTI and TxDOT staff determined the need for large open-dialogue meetings between many of the pavement marking stakeholder groups in Texas. As a result, TTI hosted two pavement marking conferences as part of 2001 research activities. A complete report detailing the proceedings from these conferences exists in (*16*).

The goal of the conferences was to identify issues and corresponding solutions related to pavement markings in Texas. Many key pavement marking stakeholders in Texas attended these conferences, including TxDOT staff (districts, traffic operations, materials, maintenance), contractors, industry personnel, and national experts. The purpose of the first conference, held in April 2001, was to allow stakeholders to present and discuss the various issues involving pavement markings on TxDOT highways. The second conference included presentations from representatives of six out-of-state DOTs detailing their respective states' performance-based pavement marking program.

One of the main issues discussed at both conferences was the poor performance of pavement markings on sealcoated roadways. The major issue raised by many TxDOT personnel was that thermoplastic markings on newly sealcoated roadways were not maintaining suitable levels of retroreflectivity. Participants proposed many potential solutions, including:

- increase thermoplastic thickness on new sealcoat (minimum 100 mil was suggested),
- apply paint as primer prior to thermoplastic striping,
- allow greater cure time for sealcoat prior to thermoplastic striping by using paint as a temporary marking, and
- initially apply paint or thin application of thermoplastic and restripe with thermoplastic the following year as part of the district restripe program.

The suggestions from these meetings aided TTI researchers in identifying research issues and development of corresponding field evaluations.

SUMMARY OF ISSUES

Maintaining pavement markings with suitable levels of retroreflectivity on sealcoats, both initially and throughout the life of the marking, has been a major challenge for TxDOT. The quality of pavement markings on sealcoat is likely influenced by certain attributes of the sealcoat surface itself, including:

- aggregate size,
- surface voids,
- surface texture, and
- length of sealcoat curing time prior to striping.

The following subsections provide a summary of the issues affecting performance of pavement markings on sealcoats, which are based on observations by researchers, TxDOT personnel, industry personnel, and pavement marking contractors. It should be noted that the issues listed here are not intended to be exhaustive, as other phenomena may exist that have not been identified by the researchers.

Issues Related to Sealcoat Surface Texture

The surface voids and irregularities on a sealcoat surface may have the greatest affect on pavement marking performance. Preliminary observations have shown that greater sealcoat surface texture often leads to both poorer retroreflectivity and durability. This poor performance likely occurs because larger spacing between sealcoat aggregates tends to allow for the pavement marking materials to fall into these voids where aggregates may shadow the material from headlamp illumination. Figure 8 shows a typical 100 mil thermoplastic edge line marking on a new Grade 3 sealcoat surface.

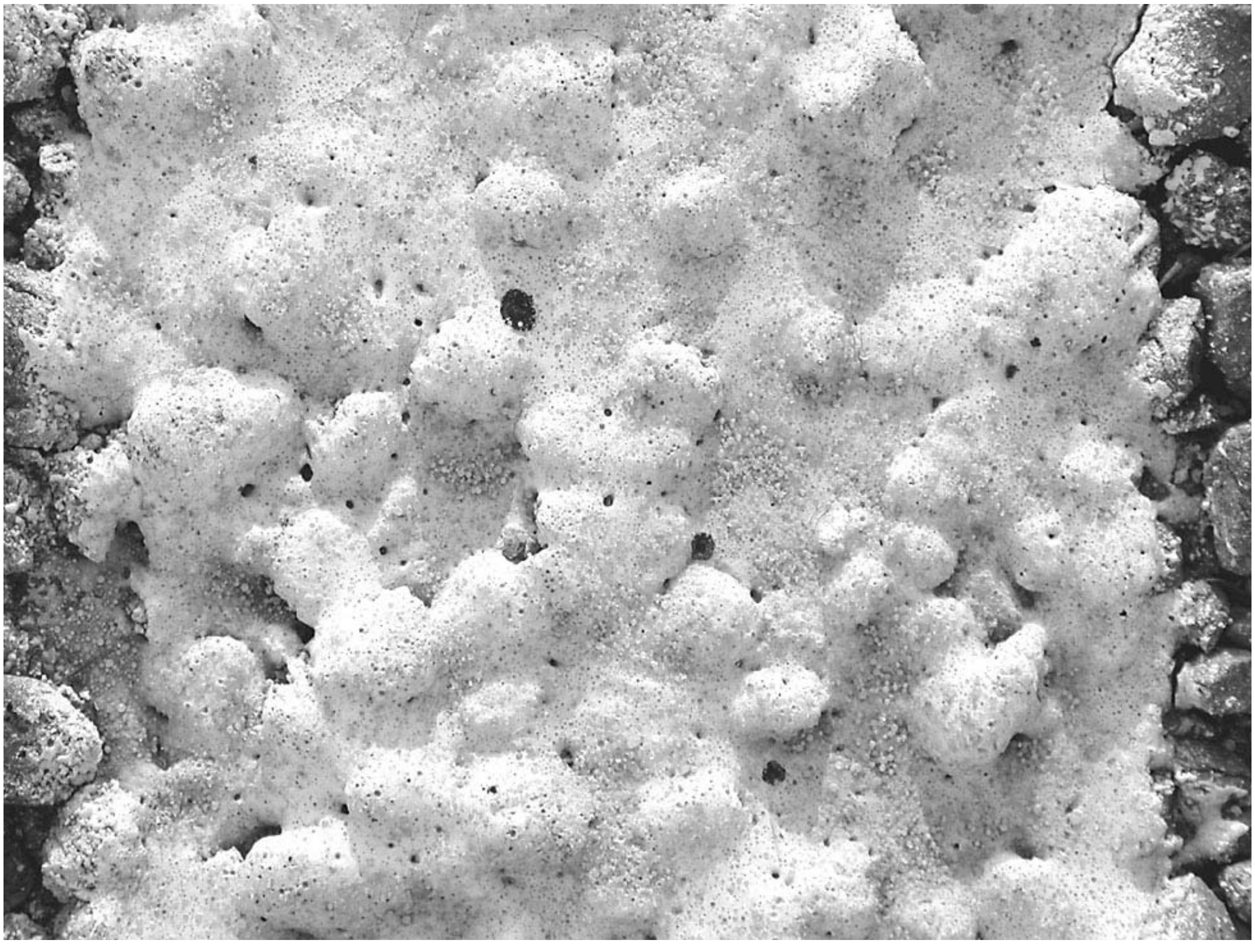


Figure 8. Typical 100 mil Thermoplastic Marking on New Grade 3 Sealcoat Surface.

The sealcoat texture may become even more of a problem as TxDOT continues the trend of using larger sealcoat aggregates (i.e., Grade 3 aggregate gradation as opposed to Grade 4) and open-graded aggregate mixes (i.e., uniform gradations, which are referred to in TxDOT specifications as “modified” gradations). Table 3 and Figures 9-12 display some of the issues related to sealcoat surface texture that TTI researchers observed during the preliminary field investigations. Countermeasures addressing sealcoat surface texture have been evaluated as part of this research and are reported later in the text.

Table 3. Pavement Marking Issues Related to Sealcoat Surface Texture.

Problem	Cause
Lower overall retroreflectivity	A high percentage of the binder and beads falls into the surface voids and crevices where shadowed by aggregates (Figure 9).
Material has worn off from tops of aggregates	Exposed binder material on top of aggregate results in material wearing off quickly (Figure 10).
Poor retroreflectivity on backside of aggregate	The momentum of the striping truck causes the frontsides of the aggregates to receive ample binder and bead coverage, while the backsides remain uncoated (Figure 11).
Bead loss on top of aggregates	Thin binder material on top of the aggregates results in poor bead embedment and adhesion (Figure 12).

Figure 9. Beads Falling between Aggregates.

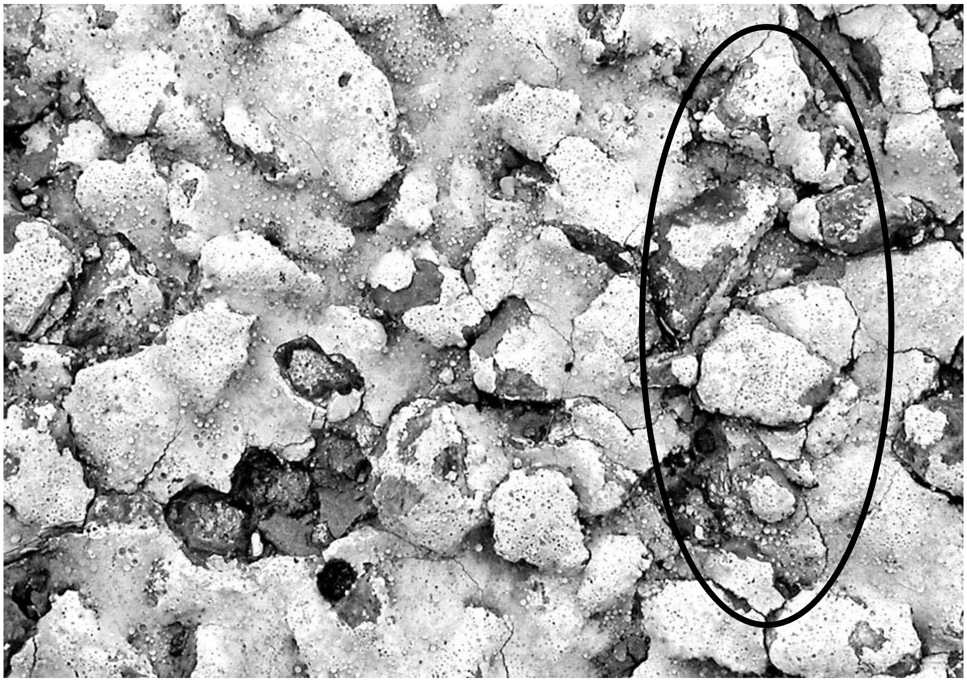


Figure 10. Poor Material Durability on Top of Aggregates.

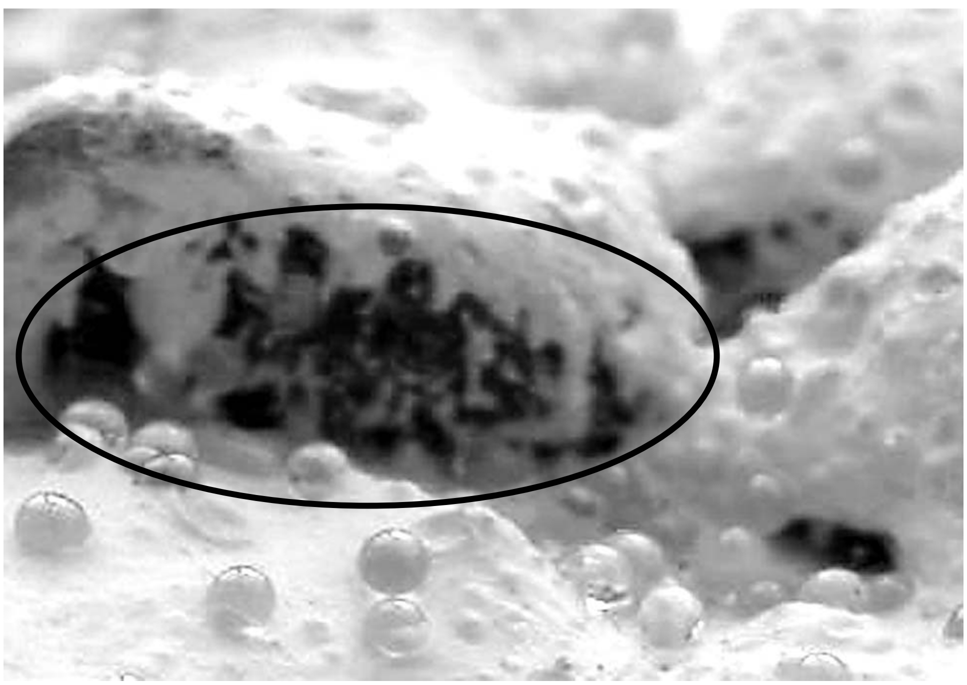


Figure 11. Poor Material Coverage on Backside of Aggregate.

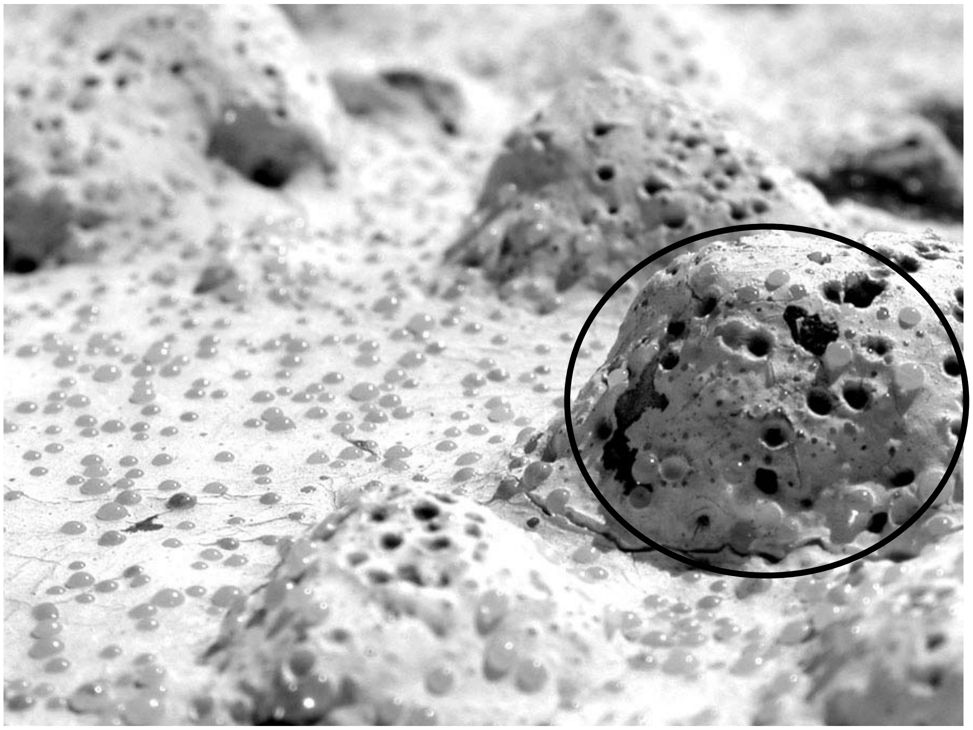


Figure 12. Poor Bead Retention on Top of Aggregates.

Issues Related to Asphalt Binder Materials for Sealcoat

Curing of a sealcoat surface occurs when solvents from the asphalt cement evaporate, causing the binder to harden and develop consistency. The rate of curing is influenced by the evaporation rate of the solvent, the amount of solvent, the viscosity of the asphalt, the temperature of the surrounding environment, the surface area of the pavement, and the wind velocity (*17*). Prior to completion of the curing process, the asphalt material is of a lower viscosity, which limits binding and allows aggregates to roll over and pop out. Uncured asphalt often bleeds to the pavement surface, as well.

The researchers performed a limited amount of research into issues pertaining to asphalt binder materials. Pavement marking problems related to the sealcoat asphalt binder should be treated at the local level due to the statewide variations in asphalt grade, asphalt quality, sealcoat construction practices, environmental conditions, and traffic conditions. Table 4 and Figures 13-15 display some of the sealcoat pavement marking problems associated with the asphalt binder material.

Table 4. Pavement Marking Issues Related to Sealcoat Binder Material.

Problem	Cause
Aggregate-sized holes in marking material	Uncured asphalt allows loose aggregates to pop out from the surface, removing portions of the markings (Figure 13).
Spots of asphalt on markings	Sprayed hot thermoplastic often boils the asphalt to the surface of the marking (Figure 14).
Markings covered with asphalt	Uncured asphalt bleeds to the pavement surface and is tracked onto markings (Figure 15).

Figure 13. Pavement Marking on Sealcoat with Aggregate Roll and Pop-Out.

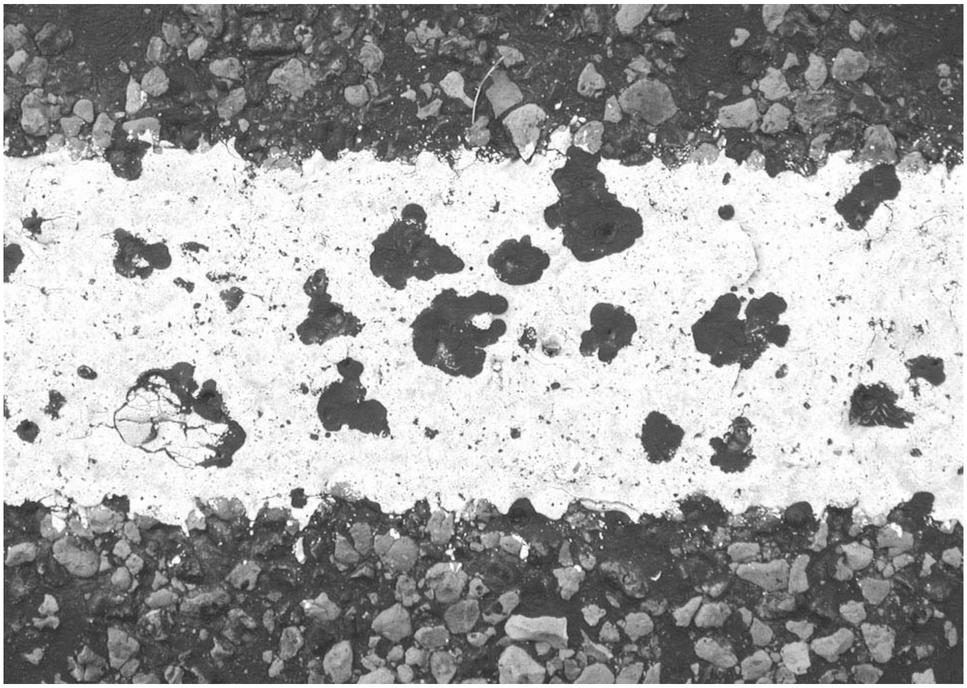


Figure 14. Asphalt Boiled through Hot Thermoplastic.

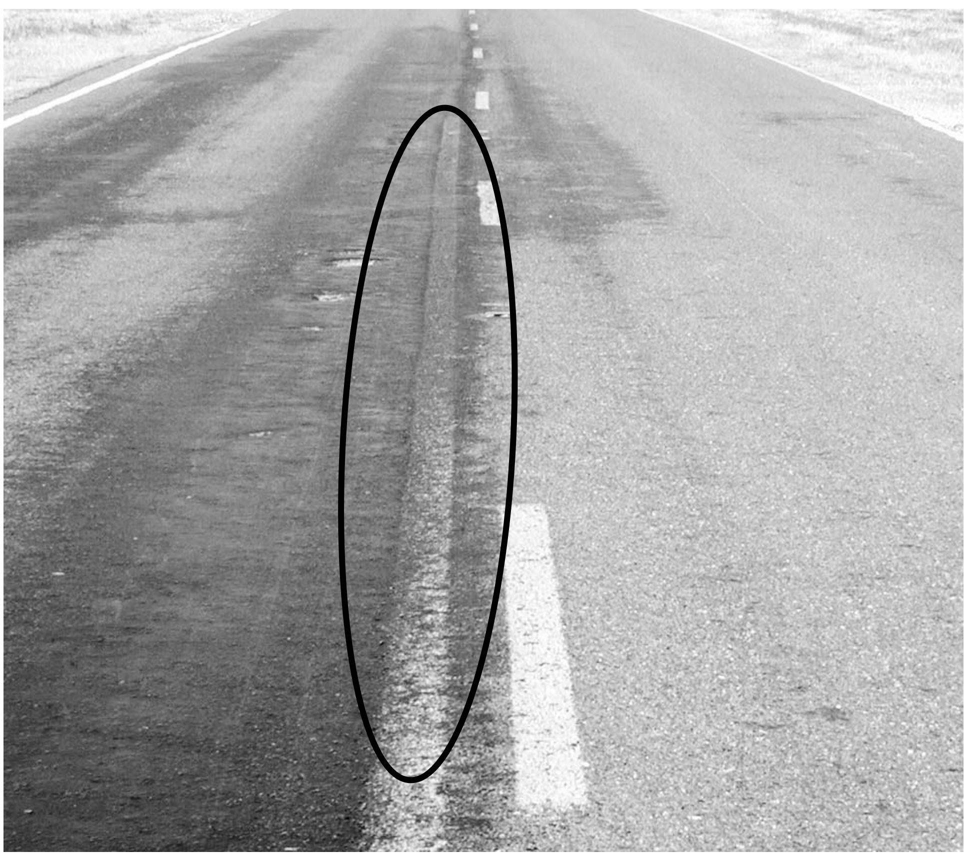


Figure 15. Asphalt Tracked onto Markings.

CHAPTER 4:
FIELD EVALUATION OF PAVEMENT MARKING APPLICATIONS

The researchers used the information obtained from the literature review, district survey, stakeholder meetings, and preliminary investigations of in-service pavement markings to develop field evaluations of various pavement marking treatments. Table 5 lists the characteristics of the field evaluations that were performed within this research project.

Table 5. Overview of Pavement Marking Field Evaluations.

Evaluation Number	Purpose	Location
1	Evaluate effect of pavement surface texture on thermoplastic initial retroreflectivity (restripe)	SH 64 near Tyler
2	Evaluate effect of pavement surface texture on thermoplastic retroreflectivity over time	FM 159 and FM 1179 near Bryan
3	Determine optimum thermoplastic thickness on new sealcoat	US 79 near Franklin
4	1.) Compare the performance of 100 mil thermoplastic vs. HD-21 acrylic resin paint on new sealcoat 2.) Determine the effects of using HD-21 paint as a surface primer prior to 100 mil thermoplastic on new sealcoat 3.) Compare retroreflectivity of 100 mil thermoplastic with larger glass beads vs. TxDOT standard specification beads on new sealcoat	US 90 and FM 365 near Beaumont
5	1.) Compare retroreflectivity of 100 mil thermoplastic with larger glass beads vs. TxDOT standard specification beads on new sealcoat 2.) Determine effect of sealcoat aggregate size on thermoplastic retroreflectivity	Various locations within the Waco District

EVALUATION METHODOLOGY

Retroreflectivity of pavement markings was the primary measure of effectiveness for the evaluations performed in the research described here. In most of these field evaluations, researchers measured the retroreflectivity of newly applied pavement markings and monitored the performance of the markings over time, although multiple site visits were not always feasible.

Each evaluation included experimental pavement marking treatments. Within each treatment section, at least one evaluation checkpoint area was selected at random. A typical pavement marking evaluation at each checkpoint included:

- 20 retroreflectivity measurements per line type (20 in each direction for yellow centerline);

- visual inspections of each line, including photographs; and
- completion of a standard evaluation form.

Retroreflectivity measurements were taken according to ASTM specification D-6359-99. Paint marks were placed as close to the exact measurement locations as possible so retroreflectivity could be tracked over time. Retroreflectivity was measured only in the direction of traffic, with the exception of yellow centerlines, which were measured in both directions to detect differences in directional retroreflectivity.

EVALUATION #1: PAVEMENT SURFACE TEXTURE INVESTIGATIONS

It has long been hypothesized that the rough-textured surface characteristics of newly sealcoated roadway surfaces are detrimental to pavement marking retroreflectivity when compared to markings on HMAC surfaces, which are much smoother. To verify this hypothesis, the researchers performed a field evaluation comparing thermoplastic retroreflectivity on rough vs. smooth pavement surfaces. The evaluation took place in March 2001 on State Highway 64 west of Tyler, Texas.

Description of Evaluation

To isolate the effect of pavement surface texture, the evaluation was performed on a section of standard thermoplastic applied on adjoining sections of HMAC and sealcoat. Table 6 presents the main attributes of this field evaluation. Figure 16 displays the macro surface texture of the white thermoplastic marking on HMAC (left) vs. sealcoat (right).

Table 6. Attributes of Evaluation #1.

Location	SH 64, west of Tyler, Texas
Roadway Type	Two-way, two-lane rural highway with shoulders
Evaluation Date	March 30, 2001
Length of Section	100 ft (50 ft HMAC, 50 ft sealcoat)
Age of Pavement Markings	14 days
Striping Condition	Restripe
Beads	TxDOT Type II
Specified Marking Thickness	100 mil
Experimental Variable	• Pavement Surface Type 1. HMAC 2. Sealcoat (Grade 4)
Measure of Effectiveness	• Initial Retroreflectivity

Figure 16. Thermoplastic Marking on HMAC vs. Sealcoat.

Analysis

Researchers took a total of 49 retroreflectivity measurements on both white and yellow markings and on both pavement surfaces within the 100 ft experimental section. Because the two pavement surfaces existed adjacent to each other on a continuous section of highway and were striped in a continuous operation, the only two independent variables for the analysis were marking color/position and pavement surface, each with two levels. The descriptive statistics from the analysis appear in Table 7.

Table 7. Retroreflectivity Findings for Evaluation #1.

Marking Color	Pavement Surface	Retroreflectivity (mcd/m²/lx)		
		Mean	Std. Deviation	N
White	Sealcoat	327.70	51.69	10
	HMAC	425.90	13.06	10
Yellow	Sealcoat	171.93	50.13	15
	HMAC	276.64	37.04	14

Results

Figure 17 shows a graphical representation of the retroreflectivity averages and 95 percent confidence intervals for the averages.

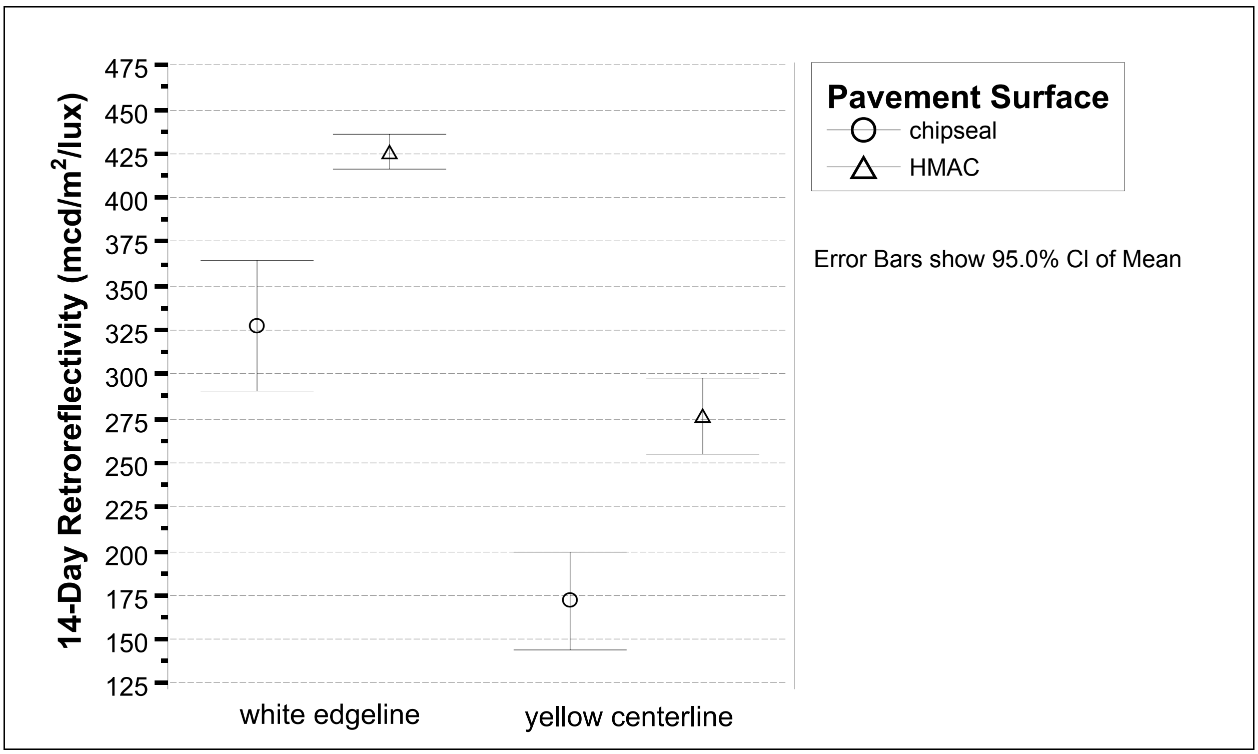


Figure 17. 14-Day Retroreflectivity vs. Pavement Surface Type and Marking Color.
Figure Note: Overlapping confidence intervals (CI) indicate no statistical difference between the populations.

Figure 17 shows that significant differences in thermoplastic retroreflectivity existed between the two pavement surfaces. The effect of pavement surface on retroreflectivity was of approximately the same magnitude for both white and yellow markings. Retroreflectivity of the sealcoat markings was approximately 98 mcd/m^2/lx (23 percent) less and 105 mcd/m^2/lx (38 percent) less than on HMAC for white and yellow, respectively. Comparison of the standard deviations in Table 7 shows that HMAC surfaces also provided more uniform retroreflectivity than sealcoat.

Summary of Findings

Due to the relatively small sample sizes, the findings resulting from this evaluation should be used with discretion:

- Thermoplastic pavement markings on HMAC had higher levels of retroreflectivity after 14 days than the same thermoplastic markings on sealcoat. This variation is likely attributed to the difference in surface texture between the two pavement surfaces.
- The effect of pavement surface texture on retroreflectivity was of similar magnitude for both white and yellow markings.
- Markings on HMAC had greater retroreflective uniformity than markings on sealcoat.

EVALUATION #2: EFFECT OF PAVEMENT SURFACE TEXTURE ON THERMOPLASTIC RETROREFLECTIVITY

Based on the results of the Tyler surface texture evaluation, a second evaluation was organized to investigate the long-term effects of pavement surface roughness on thermoplastic retroreflectivity. Local sites were selected so that retroreflectivity could be monitored frequently. The evaluation took place between June 2001 and April 2003 on FM 1179 (new HMAC) in Bryan, Texas, and FM 159 (new Grade 4 sealcoat) in Millican, Texas.

Description of Evaluation

The purpose of the experiment was to compare standard thermoplastic striping on a new sealcoat surface to standard thermoplastic striping on a new HMAC surface, using identical materials. Therefore, both roadways were striped according to TxDOT thermoplastic specifications that were current at the time. Consequently, the thermoplastic thickness on FM 1179 (HMAC) was 90 mil for all lines, while FM 159 (sealcoat) was striped at 60 mil on the edge line (EL) and 90 mil on the centerline (CL). Table 8 presents the main attributes of this field evaluation.

Table 8. Attributes of Evaluation #2.

Locations	FM 1179, in Bryan, Texas FM 159, near Millican, Texas
Roadway Types	FM 1179: Five-lane undivided urban highway with two-way left-turn lane FM 159: Two-lane rural highway
Average Daily Traffic (ADT)	FM 1179: 20,000 FM 159: 650
Evaluation Periods	Multiple between June 2001 and April 2003
Striping Conditions	New Pavement Surfaces
Beads	TxDOT Type II
Specified Marking Thickness	FM 1179: 90 mil all lines FM 159: 60 mil edge line, 90 mil centerline
Experimental Variable	• Pavement Surface Type 1. HMAC 2. Sealcoat (Grade 4) • Centerline Measurement Direction 1. With Direction of Striping (Frontside) 2. Opposite Direction of Striping (Backside)
Measures of Effectiveness	• Initial Retroreflectivity • Retroreflectivity over Time • Percent Change in Retroreflectivity over Time

Striping Operation

The experiment was organized so that a single striping crew would stripe FM 1179 (new HMAC) and, shortly after, stripe FM 159 (new sealcoat) using identical materials. The same crew, truck, and materials were used at both sites. As a quality control measure, thermoplastic samples were periodically pulled from the roadway, and measurements were made to ensure the specified thermoplastic thickness was being achieved.

Site Visits

Researchers performed at least 27 site visits for retroreflectivity evaluation at each site between June 2001 and April 2003. One checkpoint location was chosen at random at each site. Twenty retroreflectivity measurements were taken on each line-type within each checkpoint area. White edge line and lane line (LL) retroreflectivity was measured only in the direction of traffic. Yellow centerlines were measured in both directions, with 20 measurements per direction. Table 9 displays the characteristics of each site.

Table 9. Site Characteristics.

	FM 1179	FM 159
Pavement Type	New Hot-Mix Asphalt Concrete	New Grade 4 Sealcoat
Thermo Thickness, White (mil)	90	60
Thermo Thickness, Yellow (mil)	90	90
Bead Type	TxDOT Type II	TxDOT Type II
Section Length	1 mile	2 miles
Number of Evaluation Checkpoints	1	1
Total Number of Retroreflectivity Measurements Per Site Visit	20 white, 40 yellow	40 white, 40 yellow

Analysis

To determine the effect of pavement surface type on thermoplastic retroreflectivity both initially and over time, three separate analyses were performed:

- The *initial retroreflectivity* was analyzed as a function of the pavement surface, marking color, and measurement direction (yellow only).
- The *long-term retroreflectivity* at various time intervals was analyzed as a function of the pavement surface, marking color, and measurement direction (yellow only).
- The *percent change in retroreflectivity* at various time intervals was analyzed as a function of the pavement surface, marking color, and measurement direction (yellow only).

Initial and Long-Term Retroreflectivity

Thermoplastic retroreflectivity on sealcoat measured significantly lower than on HMAC both initially and even more so in the long term. Table 10 displays the average and standard deviation for retroreflectivity over time for white and yellow markings at each site. Figure 18 provides a graphical representation of the average retroreflectivity for white and yellow thermoplastic markings at each site.

Table 10. Average and Standard Deviation for Retroreflectivity.

		Retroreflectivity (mcd/m²/lx)					
		White LL/EL		Yellow CL – Frontside		Yellow CL – Backside	
		FM 1179 HMAC	FM 159 Sealcoat	FM 1179 HMAC	FM 159 Sealcoat	FM 1179 HMAC	FM 159 Sealcoat
Number of Measurements Per Site Visit		20	40	20	20	20	20
Average	Initial	495	395	260	225	249	166
	1-Week	493	286	276	149	263	112
	2-Week	477	259	266	157	265	127
	1-Month	430	217	237	146	241	119
	3-Month	516	198	305	133	301	113
	8-Month	458	178	259	132	248	105
	22-Month	288	145	157	108	151	87
Std. Dev.	Initial	16.6	28.2	13.5	17.0	13.8	17.3
	1-Week	18.1	28.2	11.5	19.4	11.8	19.6
	2-Week	15.1	24.5	11.5	13.7	16.7	15.9
	1-Month	15.7	21.5	16.0	15.6	17.7	12.8
	3-Month	17.8	32.9	15.4	19.0	22.8	19.8
	8-Month	32.0	40.2	12.2	19.1	11.9	18.2
	22-Month	62.5	29.0	15.6	17.9	17.1	19.3

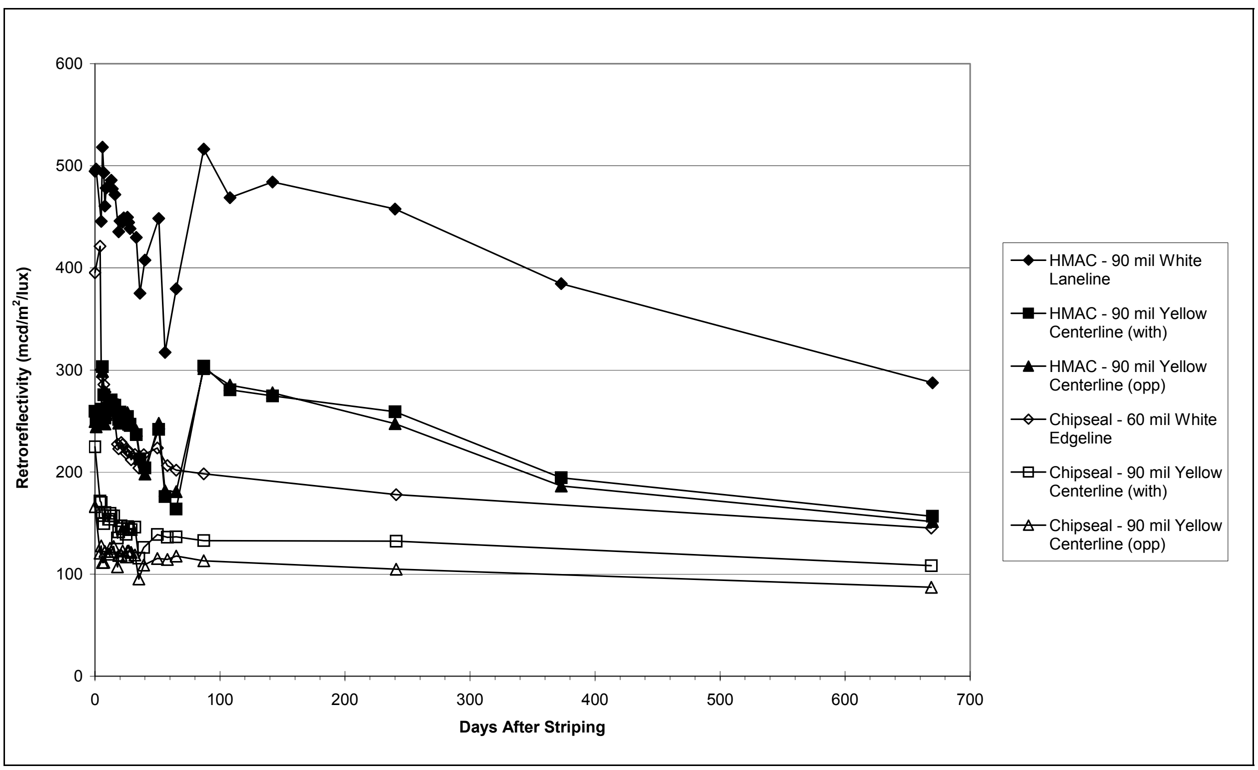


Figure 18. Average Thermoplastic Retroreflectivity vs. Time.

Table 10 and Figure 18 clearly show that thermoplastic placed on new sealcoat is significantly less retroreflective than thermoplastic placed on HMAC both initially and even more so over time, even though the traffic volume on the HMAC roadway is 30 times that of the sealcoat roadway. Additionally, comparison of the standard deviations in Table 10 shows that retroreflectivity was consistently more uniform on the HMAC surface.

Percent Change in Retroreflectivity

Table 11 displays the percent changes in retroreflectivity for white and yellow markings at each site.

Table 11. Cumulative Percent Change in Retroreflectivity.

	Cumulative Change in Retroreflectivity (percent)					
	White LL/EL		Yellow CL - Frontside		Yellow CL - Backside	
	HMAC	Sealcoat	HMAC	Sealcoat	HMAC	Sealcoat
First Week	-0.25	-27.42	6.23	-33.07	5.76	-32.38
First 10 Days	-3.25	-32.14	0.20	-31.27	2.84	-27.64
First 2 Weeks	-3.40	-34.32	2.64	-29.81	6.73	-23.04
First Month	-13.06	-44.77	-8.85	-34.70	-3.21	-28.16
First 3 Months	4.47	-49.52	17.44	-40.40	21.05	-31.26
First 8 Months	-7.35	-54.63	-0.13	-40.76	-0.10	-36.05
First 22 Months	-41.82	-63.29	-39.62	-52.00	-39.36	-47.59

Table 11 shows that thermoplastic markings on sealcoat had lost on average approximately 30 percent of their initial retroreflectivity after the first week, while their HMAC counterparts actually showed slight gains in retroreflectivity. Sealcoat markings had approached replacement retroreflectivity levels after eight months after losing approximately 36 to 55 percent of their initial retroreflectivity. After nearly two years, all markings had lost a substantial amount of retroreflectivity, although HMAC markings were still at much higher retroreflectivity levels than sealcoat markings. These findings suggest that thermoplastic markings provide superior bead retention when placed on a smoother pavement surface, such as HMAC, vs. a coarser pavement surface, such as sealcoat.

Discussion of Results

It appears that the HMAC pavement surface provides for thermoplastic retroreflectivity that is superior both initially and over time vs. similar thermoplastic markings on sealcoat.

When thermoplastic is applied to sealcoat, a large percentage of the materials (binder/beads) falls into the surface voids between the aggregates. This occurrence is detrimental to retroreflectivity both initially and over time, because:

- many of the beads that have fallen between aggregates are not capable of reflecting headlamp illumination and
- thin binder material coupled with high traffic exposure results in poor bead adhesion on top of aggregates.

Many of these phenomena are evident in Figure 19, which displays an edge line marking on FM 159 vs. a lane line marking on FM 1179. Each photo was taken two years after application.

a. Sealcoat (FM 159) **b. Hot-Mix Asphalt (FM 1179)**

Figure 19. Thermoplastic Two Years after Application.

The HMAC provides a smoother surface for the markings, thereby increasing the percentage of effective surface beads, improving bead adhesion, improving the retroreflectivity on the backsides of the marking, and providing a more uniformly retroreflective surface. Furthermore, it is likely that relative retroreflective performance would have been even poorer for sealcoat had Grade 3 aggregates been used for the sealcoat surface instead of Grade 4. This prediction is due to the larger aggregate size and greater surface texture of Grade 3 sealcoat surfaces.

Large increases in retroreflectivity occurred between the second and third months for markings on the HMAC surface (Figure 18). While such large increases in retroreflectivity were unexpected, they were at least partially explainable. The markings were noted as appearing progressively dirtier during each of the site visits, and as a consequence, lower levels of retroreflectivity were observed. During the third month, many days of heavy rain occurred, resulting in cleaner markings and consequently, large increases in retroreflectivity.

Summary of Findings

- Thermoplastic pavement markings on sealcoat had lower levels of retroreflectivity both initially and in the long term vs. similar thermoplastic markings on HMAC.
  - After *one week*:
    - Sealcoat thermoplastic had lost approximately 30 percent of initial retroreflectivity levels.
    - HMAC thermoplastic had gained approximately 3 percent of initial retroreflectivity levels.
  - After *eight months*:
    - Sealcoat thermoplastic retroreflectivity had degraded to replacement levels after losing approximately 36 to 55 percent of initial retroreflectivity.
    - HMAC thermoplastic had lost only 0 to 7 percent of initial retroreflectivity levels.
- Heavy rain provided a significant cleaning effect on HMAC markings, contributing to gains in retroreflectivity that were on average 120 to 140 mcd/m^2/lx. Similar findings were not observed on sealcoat.
- Differences in directional retroreflectivity for yellow centerline markings were significantly less on HMAC vs. sealcoat, indicating better binder/bead coverage for markings on HMAC pavement surfaces.
- Markings on HMAC had greater retroreflective uniformity than markings on sealcoat.

EVALUATION #3: OPTIMUM THERMOPLASTIC THICKNESS FOR NEW SEALCOAT

The results of the HMAC/sealcoat thermoplastic comparisons performed in Evaluations #1 and #2 showed poor relative performance for retroreflectivity of standard thermoplastic markings on new sealcoat vs. new HMAC. Researchers hypothesized that retroreflective performance for thermoplastic on new sealcoat would improve by applying thermoplastic at thicknesses greater than the 60/90 mil specified by TxDOT at the time for edge lines and centerlines, respectively.

Researchers believed that increasing the thickness of thermoplastic markings would provide better retroreflectivity performance both initially and over time by:

- Leveling out the pavement marking surface, thereby increasing the percentage of effective surface beads and
- providing thicker binder material on top of the aggregates, improving bead retention.

As a result, an evaluation was performed to determine the effect of thermoplastic thickness on long-term retroreflectivity for a new sealcoat.

Description of Evaluation

Table 12 shows the attributes of the thermoplastic thickness evaluation.

Table 12. Attributes of Evaluation #3.

Location	US 79, East of Franklin, Texas
Roadway Type	Two-way, two-lane rural highway with shoulders
Length of Each Treatment Section	1 mile
Average Daily Traffic	3000
Sealcoat Aggregate	Grade 4 (precoated)
Sealcoat Date	May 21, 2001
Striping Date	June 11, 2001
Evaluation Periods	3, 37, 70, 262 days after striping
Striping Condition	New pavement surface
Beads	TxDOT Type II
Experimental Variable	• Thermoplastic Thickness 1. 60 mil (white) 2. 75 mil (white) 3. 90 mil (white and yellow) 4. 100 mil (white and yellow) 5. 110 mil (white and yellow) • Centerline Measurement Direction 1. With Direction of Striping (Frontside) 2. Opposite Direction of Striping (Backside)
Measures of Effectiveness	• Initial Retroreflectivity • Retroreflectivity @ 1-Month, 2-Months, and 9-Months • Percent Change in Retroreflectivity over Time

Researchers determined the thermoplastic thicknesses evaluated in this experiment (60 mil, 75 mil, 90 mil, 100 mil, and 110 mil) based on the judgment of TxDOT and TTI staff. The minimum thicknesses used in this evaluation (60 mil white, 90 mil yellow) were selected because they were the standard thicknesses specified by TxDOT at the time of the experiment. The maximum thickness (110 mil) was chosen based on capabilities of the striping truck. Table 13 displays the characteristics of each experimental striping section.

Table 13. Characteristics of Striping Treatment Sections.

	Treatment 1 (TxDOT Standard Application)	**Treatment 2**	**Treatment 3**	**Treatment 4**	**Treatment 5**
Thermo Thickness, White Edge Line (mil)	60	75	90	100	110
Thermo Thickness, Yellow Centerline (mil)	90	90	90	100	110
Length of Treatment Section	1-mile	1-mile	1-mile	1-mile	1-mile
Number of Evaluation Checkpoints Per Treatment	2 white, 1 yellow	2 white, 1 yellow	2 white, 1 yellow	2 white, 2 yellow	1 white, 1 yellow
Number of Retroreflectivity Measurements Per Treatment	40 white, 40 yellow	40 white, 40 yellow	40 white, 40 yellow	40 white, 80 yellow	20 white, 40 yellow

Striping Operation

The striping was performed in June 2001 on a freshly sealcoated section of US 79 east of Franklin, Texas. This experiment used only the northbound white edge line and yellow centerline. The type and brand of glass bead and thermoplastic material were held constant throughout the striping operation.

Strict quality control during striping ensured the correct experimental thicknesses. To ease the operations, the various mile-long sections of equal thickness were marked out on the pavement surface in order of ascending thickness. As a quality control measure, thermoplastic samples were periodically pulled from the roadway, and thickness measurements were made by TTI staff with a needlepoint micrometer to the top-of-binder (Figure 20). When the specified thickness had been achieved, a paint mark was made on the pavement so retroreflectivity evaluation could be performed there.

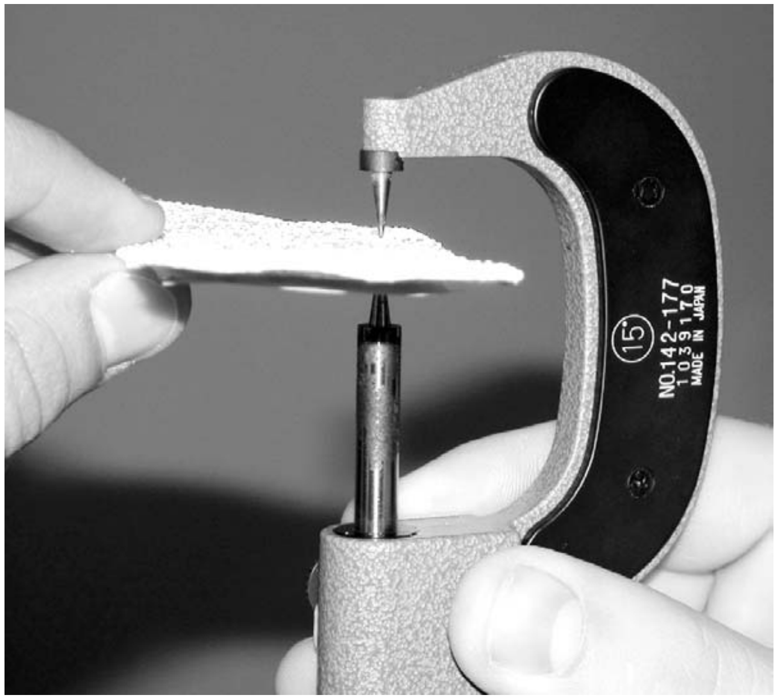


Figure 20. Thickness Measurement with Needlepoint Micrometer.

Site Visits

Four site visits for retroreflectivity evaluation were performed at this site between June 2001 and February 2002. Site visits for retroreflectivity measurement were made initially (3 days), at approximately one month after striping (37 days), approximately two months after striping (70 days), and approximately nine months after striping (255 and 262 days).

Checkpoint locations were randomly chosen at either end of each mile-long section of equal marking thickness in an attempt to provide a representative sample for a given thickness. Checkpoints were selected on relatively flat tangent sections that were away from driveways or intersections. Because no major intersections occurred over this 5-mile experimental area, traffic exposure between sections was assumed constant.

Twenty retroreflectivity measurements were taken on each line-type within a given checkpoint area. Approximately 420 retroreflectivity measurements were taken during each site visit.

Analysis

To determine the effect of marking thicknesses on thermoplastic retroreflectivity both initially and over time, many separate analyses were performed:

- The *initial (3-day) retroreflectivity, one-month retroreflectivity, two-month retroreflectivity, and nine-month retroreflectivity* were analyzed as a function of the nominal marking thickness and marking color.
- The *percent change in retroreflectivity* over time was analyzed as a function of the nominal marking thickness, time, and marking color.
- The *directional retroreflectivity* characteristics of the yellow markings were analyzed as a function of measurement direction and nominal marking thickness.

Initial and Long-Term Retroreflectivity

Thermoplastic thickness showed a significant effect on retroreflectivity, especially in the long-term. Table 14 and Figure 21 display the average initial and long-term retroreflectivity for each thickness for *white* edge line markings. Table 15 and Figure 22 display the average retroreflectivity over time for each thickness for *yellow* centerline markings.

Table 14. Average Retroreflectivity for White Edge Line.

Thermoplastic Thickness (mils)	Number of Measurements Per Section Per Site Visit	Average Initial Retro. (mcd/m^2/lx)	Average One Month Retro. (mcd/m^2/lx)	Average Two-Month Retro. (mcd/m^2/lx)	Average Nine-Month Retro. (mcd/m^2/lx)
60	40	233	172	171	132
75	40	263	201	202	209
90	40	265	216	224	244
100	40	245	223	243	238
110	20	246	208	223	244

Table 15. Average Retroreflectivity for Yellow Centerline.

Thermo. Thickness (mils)	Meas. Direction	Number of Measurements Per Section Per Site Visit	Average Initial Retro. (mcd/m^2/lx)	Average One Month Retro. (mcd/m^2/lx)	Average Two-Month Retro. (mcd/m^2/lx)	Average Nine-Month Retro. (mcd/m^2/lx)
90	Frontside	60	157	134	123	161
	Backside	60	131	117	111	134
100	Frontside	40	149	142	138	162
	Backside	40	142	139	138	151
110	Frontside	20	164	150	146	169
	Backside	20	155	141	140	158

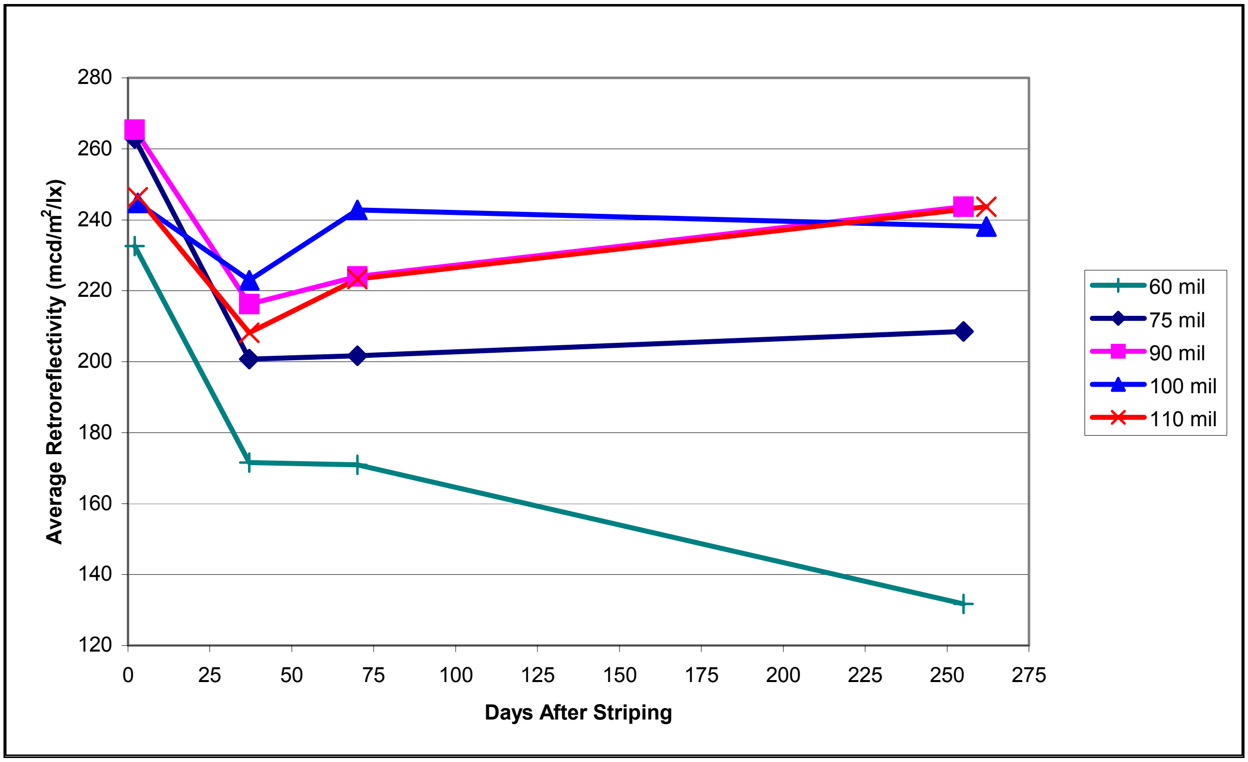


Figure 21. Average Retroreflectivity for White Edge Line.

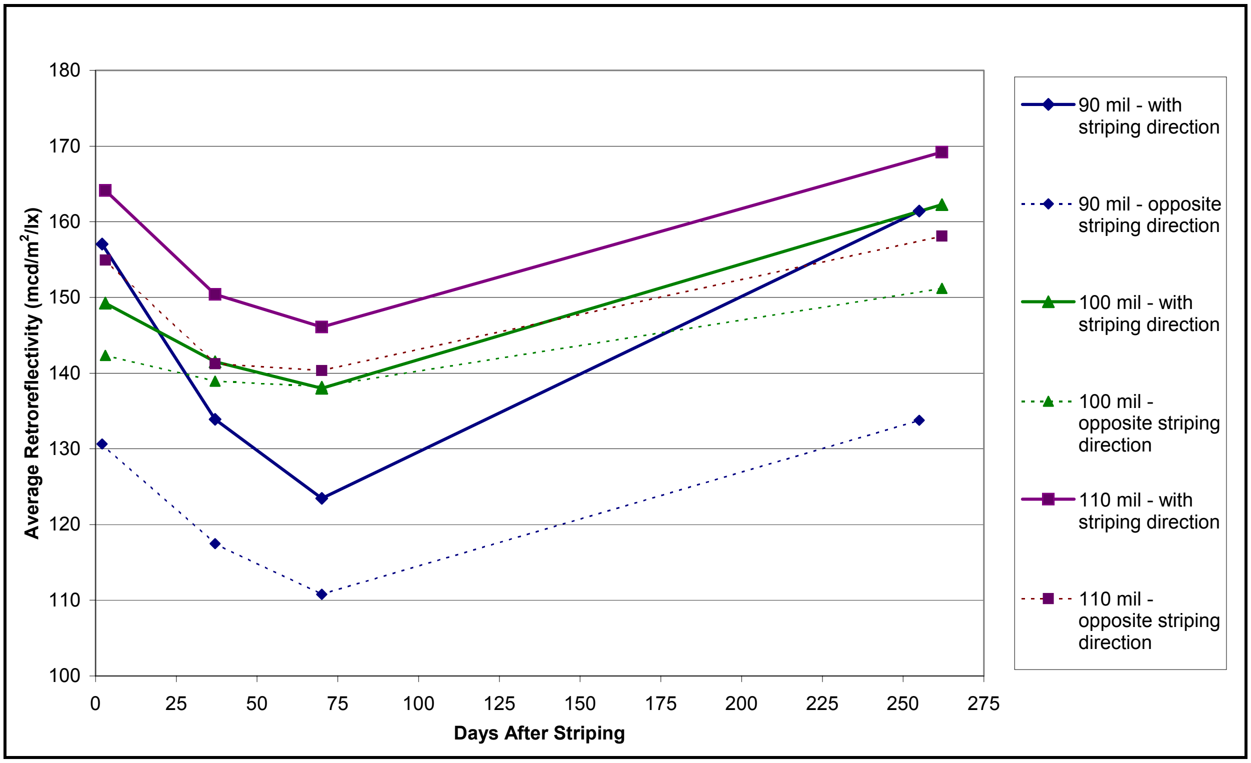


Figure 22. Average Retroreflectivity for Yellow Centerline.

It can be observed in the preceding tables and figures that for nearly every marking thickness, retroreflectivity declined significantly over the first month, but leveled off after one month, and in many cases began to increase after the first or second month. The retroreflectivity degradation was generally less pronounced for thicker markings.

Statistical analysis showed that thermoplastic thickness had a statistically significant effect on retroreflectivity both initially and over time for both white and yellow markings. Although there were significant differences in the initial retroreflectivities for the various marking thicknesses, there was no consistent correlation between marking thickness and initial retroreflectivity. However, over time thicker markings (≥ 90 mil) were found to have significantly higher retroreflectivity for both white and yellow markings, indicating better glass bead retention. It is also worth noting that after nine months, retroreflectivity of the 60 mil white edge line was approaching replacement level. Figure 23 displays the 95 percent confidence intervals for average retroreflectivity over time as a function of thickness and color.

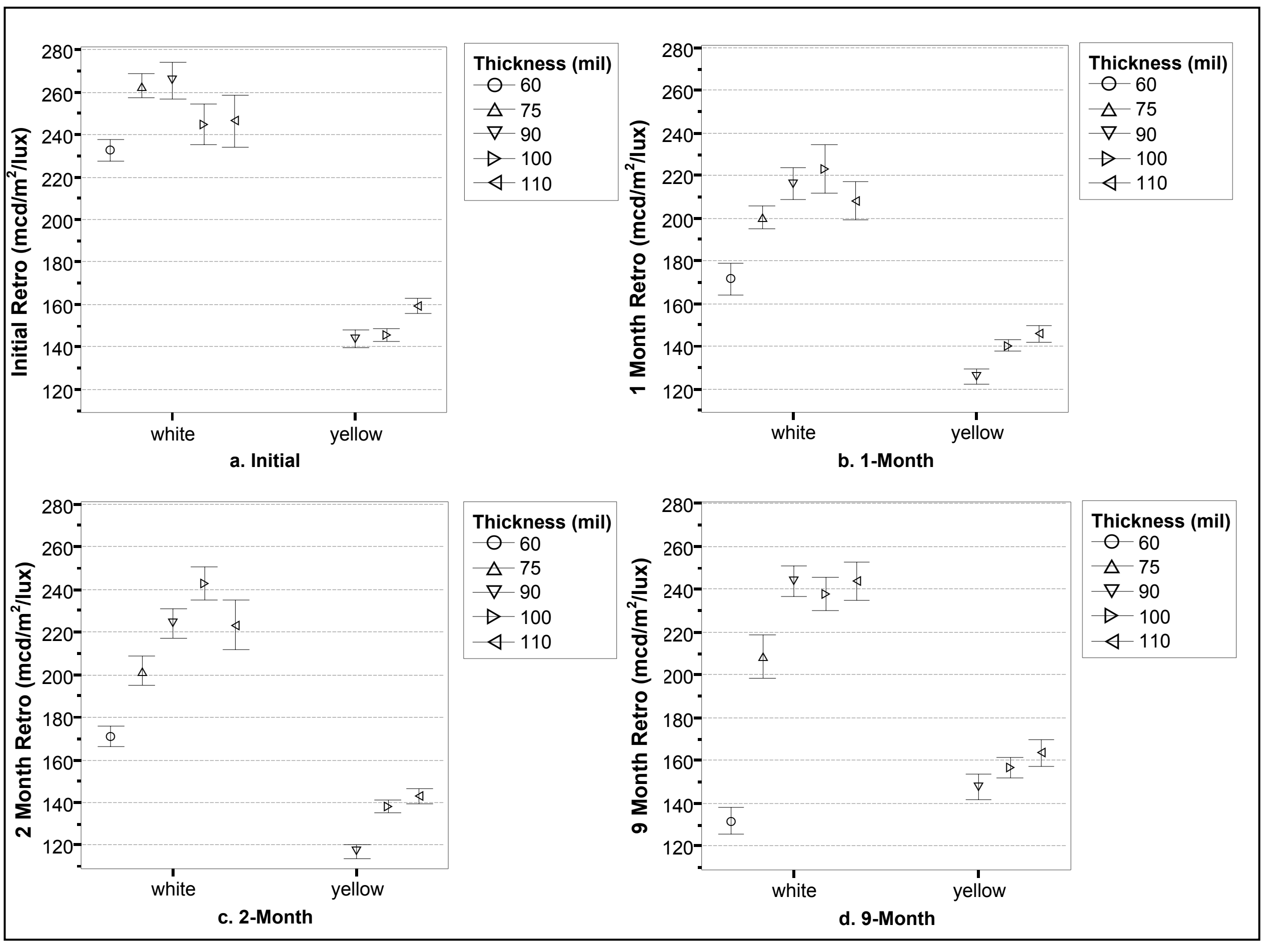


Figure 23. Confidence Intervals for Average Retroreflectivity vs. Thickness and Color.
Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Figure 23 shows that although there is no correlation between thermoplastic thickness and initial retroreflectivity, sections with thicknesses equal to or greater than 90 mil maintain greater levels of retroreflectivity in the long-term.

Change in Retroreflectivity over Time

Thermoplastic thickness was also found to have a significant effect on the rate of change in retroreflectivity, especially in the long-term. Tables 16 and 17 display the average changes in retroreflectivity as functions of thickness, time, and measurement direction (yellow only) for white and yellow markings, respectively.

Table 16. Average Change in Retroreflectivity for White Edge Line.

Thermo. Thickness (mils)	Average Retro. Change during First Month		Average Overall Retro. Change from Initial to Ninth Month	
	percent	$mcd/m^2/lx/day$	percent	$mcd/m^2/lx/day$
60	-26.2	-1.77	-43.0	-0.40
75	-23.6	-1.78	-20.2	-0.21
90	-18.4	-1.41	-7.2	-0.09
100	-8.4	-0.64	-1.6	-0.03
110	-15.1	-1.12	0.02	-0.01

Table 17. Average Change in Retroreflectivity for Yellow Centerline.

Thermo. Thickness (mils)	Meas. Direction	Average Retro. Change during First Month		Average Overall Retro. Change from Initial to Ninth Month	
		percent	$mcd/m^2/lx/day$	percent	$mcd/m^2/lx/day$
90	Frontside	-14.7	-0.66	3.2	0.01
	Backside	-9.9	-0.38	2.7	0.01
100	Frontside	-5.1	-0.23	9.0	0.06
	Backside	-1.8	-0.10	6.7	0.03
110	Frontside	-8.4	-0.40	3.3	0.02
	Backside	-8.7	-0.40	2.0	0.01

It can be observed from the preceding tables that thermoplastic thickness had a significant effect on the change in retroreflectivity over time, but only for markings equal to or greater than 90 mil. Figure 24 shows that markings with thicknesses equal to or greater than 90 mil retained initial levels of retroreflectivity during the first nine months significantly better than marking sections that were thinner than 90 mil.

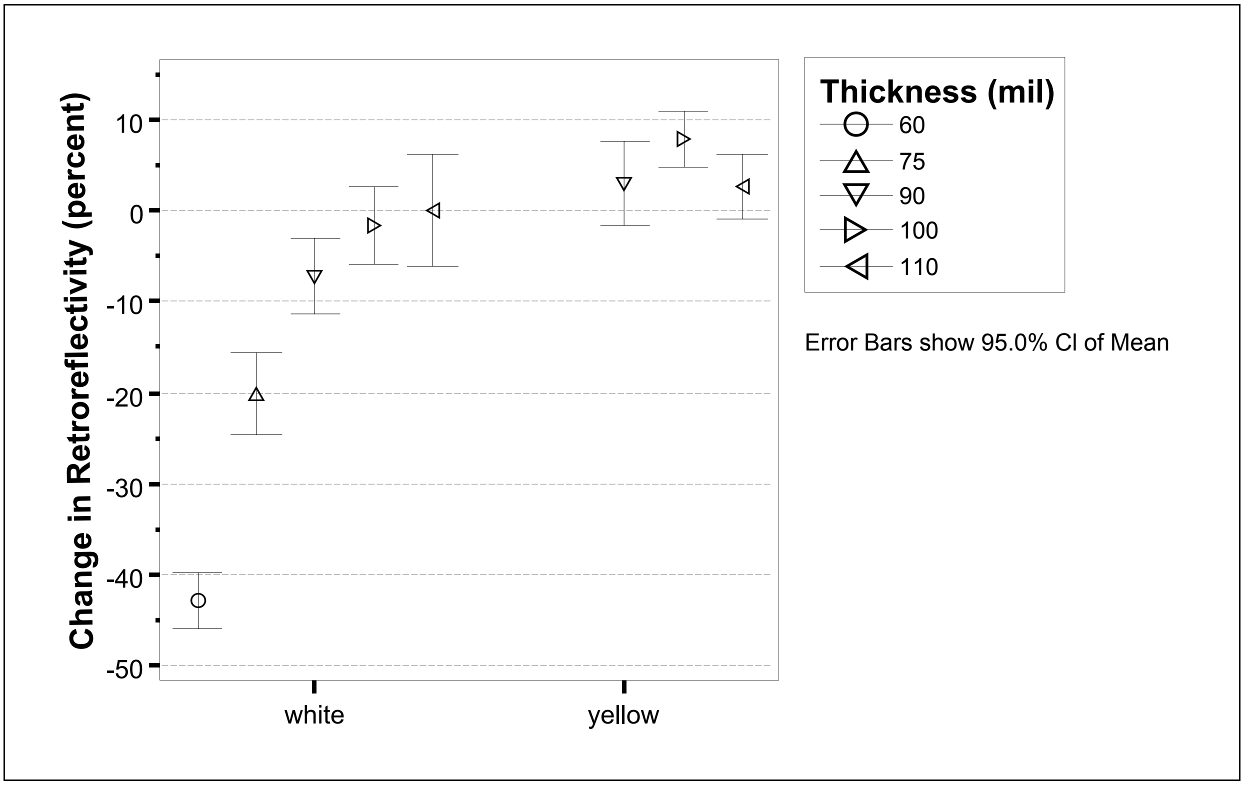


Figure 24. Confidence Intervals for Average Percent Change in Retroreflectivity during First Nine Months.

Figure Note: Overlapping of confidence intervals indicates no statistical difference between average values.

Directional Retroreflectivity for Yellow Centerlines

It is desirable for pavement markings to possess similar levels of retroreflectivity regardless of the viewing direction. This experiment has shown that thermoplastic markings possessed significantly greater retroreflectivity *with* the direction of the striping operation (frontsides) vs. *opposite* the direction of the striping operation (backsides) (see Table 15 and Figure 22). This was the case both initially and over time.

Visual observations found greater material (bead/binder) coverage on the frontsides vs. the backsides of the sealcoat aggregates, likely causing the differences in directional retroreflectivity. Visual observations also found that material coverage on the backsides of aggregates improved with increasing thermoplastic thickness. Subsequent retroreflectivity measurement showed that differences in directional retroreflectivity were less pronounced at greater marking thicknesses.

Summary of Findings

This evaluation was useful in determining the retroreflective performance of thermoplastic markings as a function of marking thickness. The following findings resulted from this evaluation.

Initial Retroreflectivity

- Thermoplastic thickness had very little effect on initial retroreflectivity levels.

Long-Term Retroreflectivity

- Thermoplastic thickness had a significant effect on long-term retroreflectivity levels:
  - Thermoplastic applied at equal to or greater than 90 mil[4] provided significantly better long-term retroreflective performance than thermoplastic applied at lesser thicknesses.
  - Better retroreflectivity was likely due to better glass bead retention provided by the thicker thermoplastic binder.
- No conclusions were drawn as to why the gains in retroreflective performance appeared to level off at thicknesses greater than 90 mil.
- Retroreflectivity of the 60 mil white edge line was approaching replacement level after nine months.

Change in Retroreflectivity over Time

- Thermoplastic retroreflectivity was found to degrade rapidly during the first month after striping, usually stabilizing after one month and increasing in many cases.
- Markings with thicknesses equal to or greater than 90 mil retained initial levels of retroreflectivity significantly better over time than markings thinner than 90 mil.

Direction Retroreflectivity for Yellow Centerlines

- For yellow centerlines, retroreflectivity measurements made *with* the direction of the striping operation were usually higher than those *opposite* the direction of striping, especially for markings that are thinner than 100 mil.

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[4] Measured to top-of-binder, excluding glass beads.

– Visual observations showed that that the frontsides of the aggregate receive better applications of material than the backsides.
– Differences in directional retroreflectivity were less pronounced at greater marking thicknesses.

EVALUTION #4: EVALUATION OF VARIOUS PAINT AND THERMOPLASTIC APPLICATIONS ON NEW SEALCOAT

To address issues involving sealcoat curing, a pavement marking experiment determined the effectiveness of standard waterbased paint used in either of the following ways:

- as a surface primer prior to thermoplastic application or
- as a temporary pavement marking.

Researchers hypothesized that using paint as a primer on a new sealcoat would provide the following advantages:

- level out the voids and gaps in the sealcoat surface, improving thermoplastic retroreflectivity;
- reduce the occurrence of asphalt boiling through thermoplastic on application; and
- provide a less costly alternative to other primer materials.

Additionally, if paint was found to provide suitable retroreflectivity for several months as a temporary pavement marking, thermoplastic could be placed at a much later date, well after the sealcoat surface had fully cured. Lengthening the time between sealcoat and thermoplastic applications would greatly reduce pavement marking problems associated with the sealcoat asphalt binder and might provide lower overall striping costs.

Objectives

The objectives of the experiment were as follows:

- determine the performance of 100 mil thermoplastic new sealcoat with large aggregates (TxDOT Grade 3),
- determine the effects of using HD-21 waterbased paint as a primer prior to thermoplastic application on new sealcoat,
- compare the long-term performance of HD-21 waterbased paint pavement markings to that of 100 mil thermoplastic pavement markings on new sealcoat,

- determine the difference in retroreflective performance of large glass beads (TxDOT Type III) vs. standard glass beads (TxDOT Type II) for 100 mil thermoplastic on new sealcoat, and
- compare the long-term performance of 130 mil thermoplastic (double application) vs. 100 mil thermoplastic (single application) on new sealcoat.

Description of Evaluation

The attributes of this experiment are found in Table 18.

Table 18. Attributes of Evaluation #4.

Location	US 90, West of Beaumont, Texas FM 365, South of Beaumont, Texas
Roadway Type	US 90: Four-lane divided rural highway without shoulders FM 365: Two-way, two-lane rural highway with shoulders
Length of Each Striping Section	2 miles
Average Daily Traffic	US 90: 14,000 FM 365: 4000
Sealcoat Aggregate	Grade 3 (precoated clay shale)
Striping Dates	May 8-12, 2001
Evaluation Periods	Initial and 130 days
Striping Condition	New Sealcoat Surface
Pavement Marking Thickness	Thermo: 100 mil Paint: 25 mil Paint used as primer: 25 mil
Beads	TxDOT Type II or TxDOT Type III
Experimental Variables	• Marking Type 1. 100 mil Thermo – Unprimed Surface 2. 100 mil Thermo – Primed Surface 3. 25 mil Paint • Thermoplastic Application 1. Single 2. Double • Marking Position 1. Edge Line 2. Lane Line • Glass Bead Type 1. TxDOT Type II 2. TxDOT Type III (unprimed thermo only) • Centerline Measurement Direction 1. With Direction of Striping (Frontside) 2. Opposite Direction of Striping (Backside)
Measures of Effectiveness	• Initial Retroreflectivity • Four-Month Retroreflectivity • Percent Change in Retroreflectivity over Time

Roadway Characteristics

The evaluation occurred on two different freshly sealcoated roadways, (FM 365 and US 90) in the Beaumont, Texas, area. FM 365 was a two-lane rural highway with wide shoulders and an ADT of 4000. US 90 was a four-lane divided highway with no shoulders and a directional ADT of 14,000. The two roadways were selected primarily due to their different levels of traffic.

Pavement Marking Treatments

Four different pavement marking treatment sections were applied to each roadway. The same materials and application properties were used for all lines within a given section. In addition, the striping materials and properties for a given section were identical between the two roadways. Each treatment section was approximately 2 miles in length. Table 19 displays the material and application characteristics of the pavement markings for each of the experimental striping sections on both highways.

Table 19. Characteristics of Striping Treatment Sections.

	Treatment 1	Treatment 2	Treatment 3	Treatment 4
Marking	Waterbased Paint	Thermo (Paint Primer)	Thermo (Unprimed)	Thermo (Unprimed)
Marking Thickness (mil)	25	100	100	100
Beads	TxDOT Type II	TxDOT Type II	TxDOT Type II	TxDOT Type III

Site Visits

Site visits were made initially and after four months to evaluate the various pavement marking treatments. Two checkpoint locations were randomly chosen at either end of each treatment section in an attempt to provide a representative sample for a given treatment. Twenty retroreflectivity measurements were taken on each line type within a given checkpoint area. Table 20 describes the evaluation characteristics for each site.

Table 20. Characteristics of Retroreflectivity Evaluation.

	US 90	FM 365
Markings Included in Evaluation	WB White Edge Line, WB White Lane Line, WB Yellow Edge Line	EB White Edge Line, WB White Edge Line, Yellow Centerline (both directions)
Number of Checkpoints per Section	2	2
Number of Retroreflectivity Measurements per Line Type per Section	40	40

Analysis

To determine the effect of the various pavement marking treatments on retroreflectivity both initially and over time, many analyses were performed.

- The *initial retroreflectivity* and *4-month retroreflectivity* were analyzed as a function of the site, material type, color, position on roadway, marking thickness, glass bead size, and primer.
- The *percent change in retroreflectivity* was analyzed as a function of the site, material type, color, position on roadway, marking thickness, glass bead size, and primer.

Initial and 4-Month Retroreflectivity

Tables 21 and 22 display the average retroreflectivity for white and yellow markings for US 90 and FM 365, respectively.

Table 21. Average Initial and 4-Month Retroreflectivity, US 90.

Sec. No.	Treatment	White Edge Line		White Lane Line		Yellow Edge Line	
		Average Initial Retro. (mcd/m^2/lx)	Average Four-Month Retro. (mcd/m^2/lx)	Average Initial Retro. (mcd/m^2/lx)	Average Four-Month Retro. (mcd/m^2/lx)	Average Initial Retro. (mcd/m^2/lx)	Average Four-Month Retro. (mcd/m^2/lx)
1	25 mil Waterbased Paint w/ Std. Beads	233	200	304	233	123	90
2	100 mil Thermo w/ Std. Beads & Paint Primer	346	203	292	304	225	179
3	100 mil Themo w/ Std. Beads & No Primer	321	248	311	312	234	201
4	100 mil Thermo w/ Large Glass Beads & No Primer	293	180	368	296	202	153

Table 22. Average Initial and 4-Month Retroreflectivity, FM 365.

Sec. No.	Treatment	White Edge Line		Yellow Centerline – Frontside		Yellow Centerline – Backside	
		Average Initial Retro. (mcd/m^2/lx)	Average Four-Month Retro. (mcd/m^2/lx)	Average Initial Retro. (mcd/m^2/lx)	Average Four-Month Retro. (mcd/m^2/lx)	Average Initial Retro. (mcd/m^2/lx)	Average Four-Month Retro. (mcd/m^2/lx)
1	25 mil Waterbased Paint w/ Std. Beads	238	171	104	80	72	57
2	100 mil Thermo w/ Std. Beads & Paint Primer	394	408	206	227	199	211
3	100 mil Themo w/ Std. Beads & No Primer	381	404	213	229	221	225
4	100 mil Thermo w/ Large Glass Beads & No Primer	333	378	267	249	217	196

Statistical analysis showed that the type of material, color, and position on the roadway had a highly significant effect on retroreflectivity both initially and after four months for both white and yellow markings. Figures 25 and 26 display the 95 percent confidence intervals for average retroreflectivity initially and at 4 months as a function of marking type (denoted by section number), color, and position on the roadway.

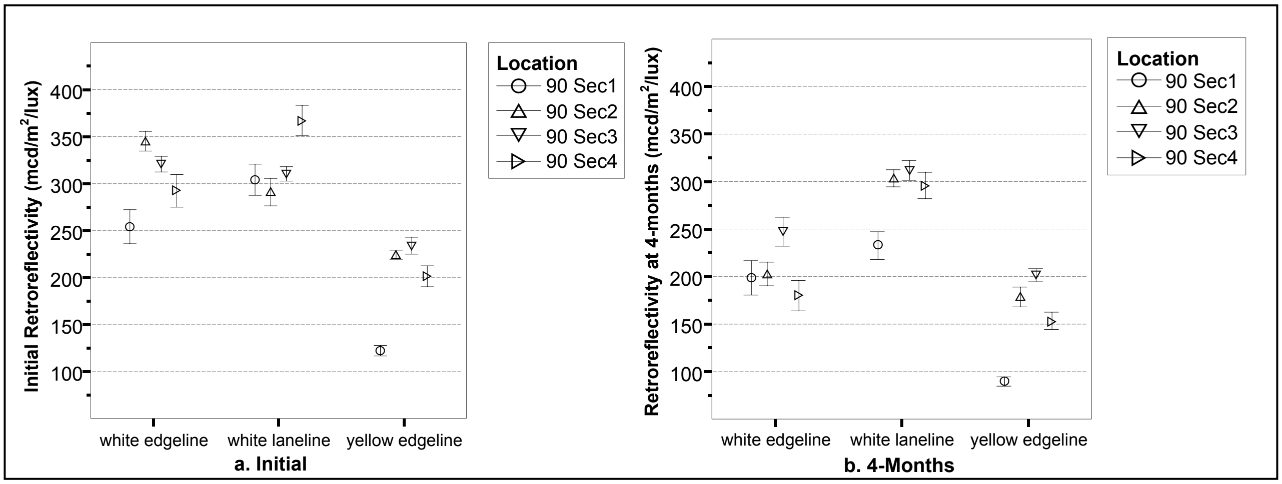


Figure 25. Confidence Intervals for Average Retroreflectivity, US 90.

Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

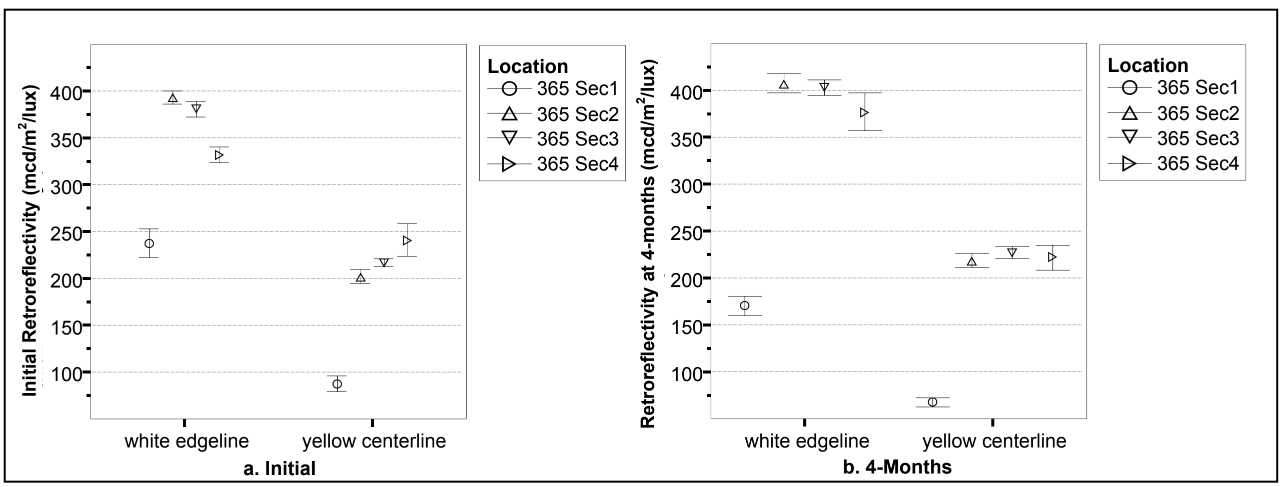


Figure 26. Confidence Intervals for Average Retroreflectivity, FM 365.

Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Change in Retroreflectivity over First Four Months

Tables 23 and 24 display the average percent change in retroreflectivity for white and yellow markings for US 90 and FM 365, respectively.

Table 23. Average Change in Retroreflectivity over First Four Months, US 90.

Sec. No.	Treatment	White Edge Line		White Lane Line		Yellow Edge Line	
		Average Change (percent)	Average Rate of Change ($mcd/m^2/lx/day$)	Average Change (percent)	Average Rate of Change ($mcd/m^2/lx/day$)	Average Change (percent)	Average Rate of Change ($mcd/m^2/lx/day$)
1	25 mil Waterbased Paint w/ Std. Beads	-21.4	-0.42	-23.1	-0.53	-26.6	-0.26
2	100 mil Thermo w/ Std. Beads & Paint Primer	-41.4	-1.07	5.7	0.09	-20.6	-0.36
3	100 mil Themo w/ Std. Beads & No Primer	-22.8	-0.57	0.43	0.01	-12.3	-0.26
4	100 mil Thermo w/ Large Glass Beads & No Primer	-38.1	-0.87	-19.1	-0.55	-21.8	-0.38

Table 24. Average Change in Retroreflectivity over First Four Months, FM 365.

Sec. No.	Treatment	White Edge Line		Yellow Centerline – Frontside		Yellow Centerline – Backside	
		Average Change (percent)	Average Rate of Change ($mcd/m^2/lx/day$)	Average Change (percent)	Average Rate of Change ($mcd/m^2/lx/day$)	Average Change (percent)	Average Rate of Change ($mcd/m^2/lx/day$)
1	25 mil Waterbased Paint w/ Std. Beads	-27.6	-0.52	-20.3	-0.19	-19.3	-0.12
2	100 mil Thermo w/ Std. Beads & Paint Primer	3.9	0.11	10.6	0.16	6.6	0.09
3	100 mil Themo w/ Std. Beads & No Primer	6.5	0.18	7.9	0.12	2.1	0.03
4	100 mil Thermo w/ Large Glass Beads & No Primer	13.8	0.33	-4.1	-0.14	-5.1	-0.16

Statistical analysis showed that the type of material, color, and position on the roadway had a highly significant effect on the change in retroreflectivity over the first 4 months. Figure 27 displays the 95 percent confidence intervals for average percent change in retroreflectivity as a function of marking type (denoted by section number), color, and position on the roadway for US 90 and FM 365.

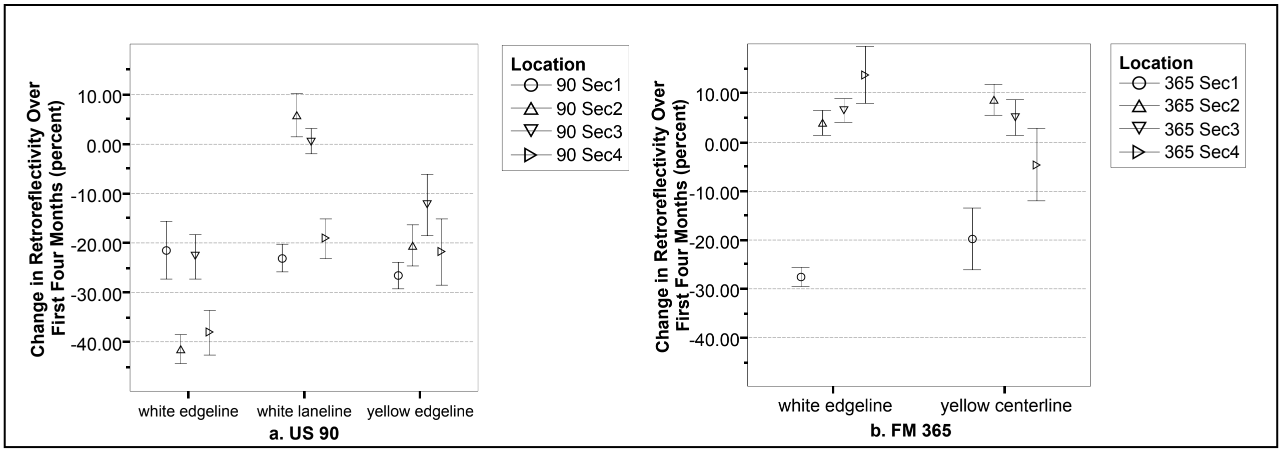
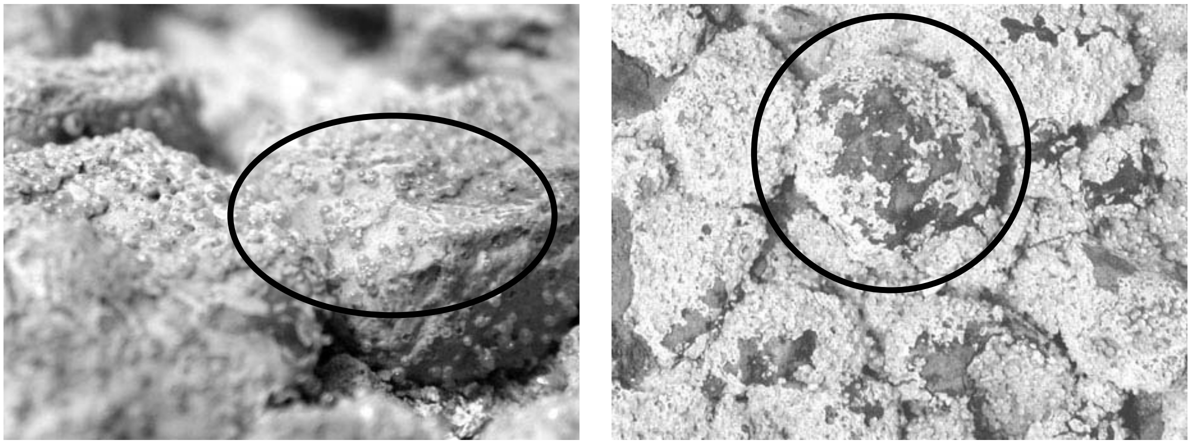


Figure 27. Confidence Intervals for Average Percent Change in Retroreflectivity.
Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Discussion of Results

Waterbased Paint vs. Thermoplastic

It can be observed in Figures 25 and 26 that for every line type except the white edge line on US 90, waterbased paint used by itself (Treatment 1) clearly provided significantly lower levels of retroreflectivity than each of the thermoplastic applications (Treatments 2-4), both initially and even more so at 4 months. Initial retroreflectivity levels for paint were up to 150 mcd/m^2/lx less than those of thermoplastic sections and were up to 225 mcd/m^2/lx less after 4 months. Each of the thermoplastic applications provided similar levels of retroreflectivity both initially and at 4 months. Figure 28 shows typical paint stripes after four months on FM 365. Note the worn appearance of the markings, which helps explain the poor retroreflectivity levels.



a. Profile View b. Top View

Figure 28. Typical Paint Pavement Markings, FM 365.

Inconsistent trends were observed for changes in retroreflectivity between the various material types, line types, and roadways (Figure 27). On FM 365, paint markings lost, on average, between 20 and 30 percent of their retroreflectivity in the first four months, while most thermoplastic marking applications showed slight gains in retroreflectivity during that time, although none of the thermoplastic applications were consistently better than the others. Increases in thermoplastic retroreflectivity over time may likely be attributed to the wearing away of excess surface beads by traffic. On US 90, which experienced much heavier traffic, paint again lost on average between 20 and 30 percent of its retroreflectivity. Nearly every thermoplastic application also experienced decreases in retroreflectivity on US 90, although no consistent trends were observed between various line types or sections.

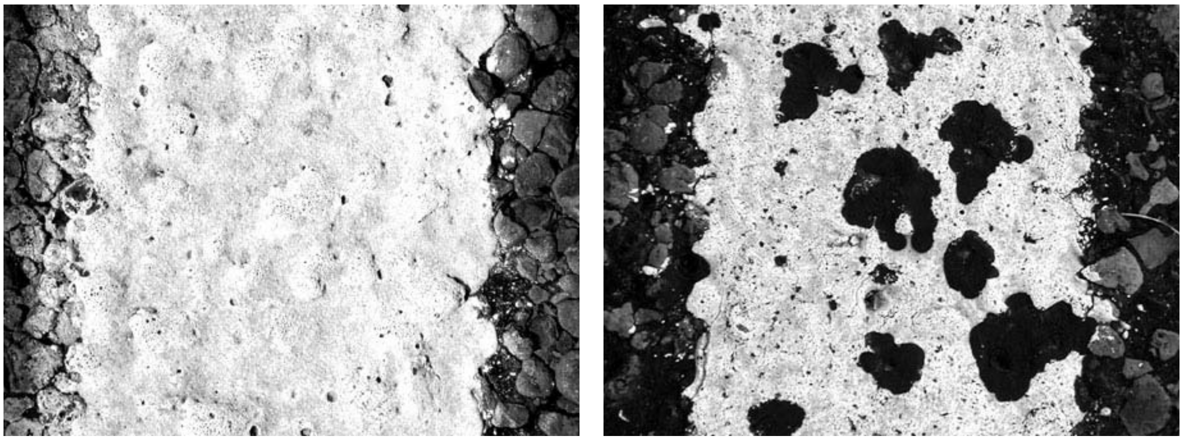
Primed vs. Unprimed Thermoplastic

Researchers hypothesized that using paint as a primer on a new sealcoat would lead to better thermoplastic performance over time by:

- filling-in voids and gaps in the sealcoat surface and
- reducing the occurrence of emulsified asphalt binder bleeding to the surface of the thermoplastic marking on application.

Comparison of the retroreflectivity data in Figures 25 and 26 from the primed (Treatment 2) vs. unprimed (Treatment 3) thermoplastic sections shows that primed thermoplastic maintained slightly higher retroreflectivity (but not statistically significant) vs. unprimed thermoplastic both initially and after four months.

Although only slight improvements in retroreflectivity were observed, the primed sections of thermoplastic did display fewer occurrences of asphalt bleeding through the thermoplastic. Figure 29 provides a comparison of typical bleeding for primed vs. unprimed sections of thermoplastic lane lines on US 90. Both photos were taken four months after striping.



a. Lane Line with Primer (Treatment 2) **b. Lane Line without Primer (Treatment 3)**

Figure 29. Asphalt Bleeding through Thermoplastic with and without Paint Primer, US 90.

It can be observed in Figure 29 that the application of a waterbased paint prior to thermoplastic application appears to impede the occurrence of emulsified asphalt bleeding through to the surface of the thermoplastic. However, small amounts of bleeding were still observed in the primed thermoplastic sections, suggesting that the primer did not completely eliminate bleeding. More experience with primers is needed before recommendations can be made.

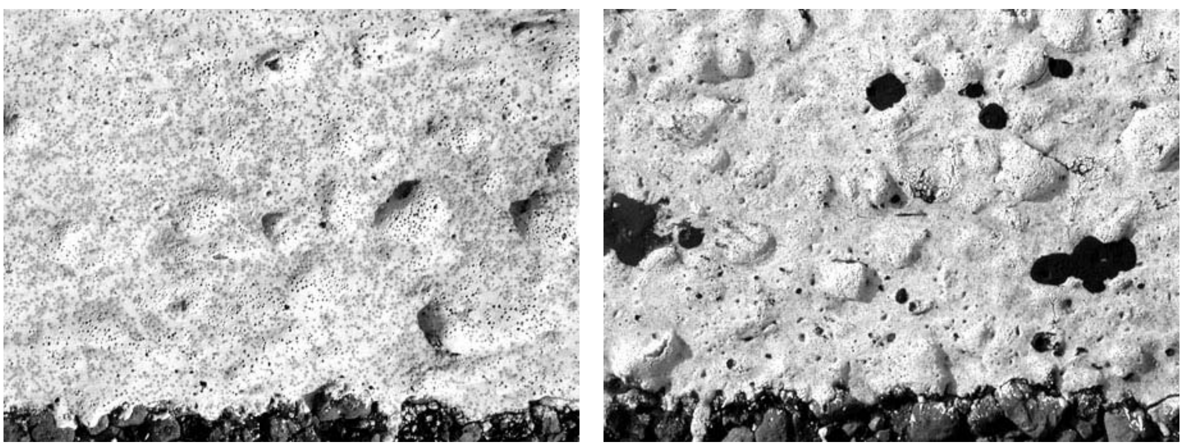
It was also noted that asphalt bled through the thermoplastic more frequently if the markings had been applied near a longitudinal joint in the sealcoat surface, including the center joint and shoulder joint. This bleeding was likely due to heavier applications of asphalt emulsion that occur near the joint due to overlapping the sealcoat surface at the joint. Edge line markings near the roadway edge experienced far less bleeding, likely due to the lighter application of asphalt there. These findings suggest that offsetting striping from longitudinal joints will reduce the occurrence of asphalt bleeding through the markings.

Standard vs. Large Glass Beads

Examination of Figures 25, 26, and 27 shows some statistically significant differences in retroreflective performance for thermoplastic with large glass surface beads (TxDOT Type III) vs. thermoplastic with smaller surface beads (TxDOT Type II). However, no consistent trends were observed between the various line types, colors, and roadways.

130 mil Thermoplastic (Doubly Applied) vs. 100 mil Thermoplastic

The thermoplastic lane line of Section 4 on US 90 was split into two mile-long sections of different thicknesses. The first mile-long section was a double application of 65 mil thermoplastic, resulting in a total thermoplastic thickness of 130 mil. The second mile-long section was a single application of 100 mil thermoplastic. All other marking characteristics were identical, and large glass beads were used in both cases. Figure 30 shows a side-by-side comparison of the two applications.



a. 130 mil Lane Line (double application) **b. 100 mil Lane Line (single application)**

Figure 30. 130 mil Thermoplastic vs. 100 mil Thermoplastic, US 90.

It can be observed from Figure 30 that the 130 mil application provided a more uniform surface coverage than the 100 mil application. The 130 mil thermoplastic markings also showed no signs of asphalt bleeding through and displayed slightly higher (although not statistically significant) retroreflectivity at four months when compared to the 100 mil thermoplastic. Figure 31 displays the 95 percent confidence intervals for average initial and 4-month retroreflectivity for the 100 mil and 130 mil thermoplastic lane line sections on US 90.

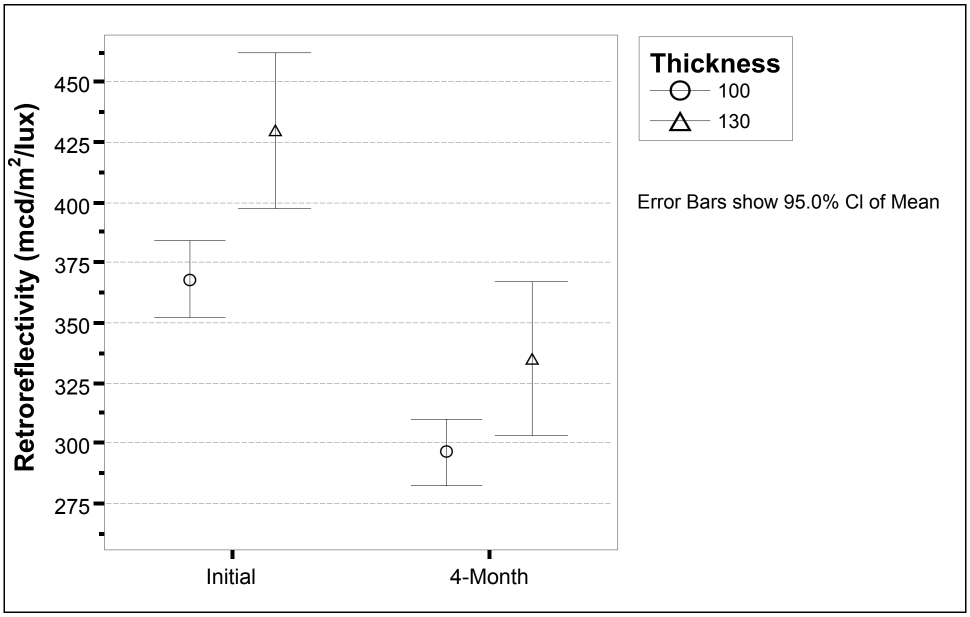
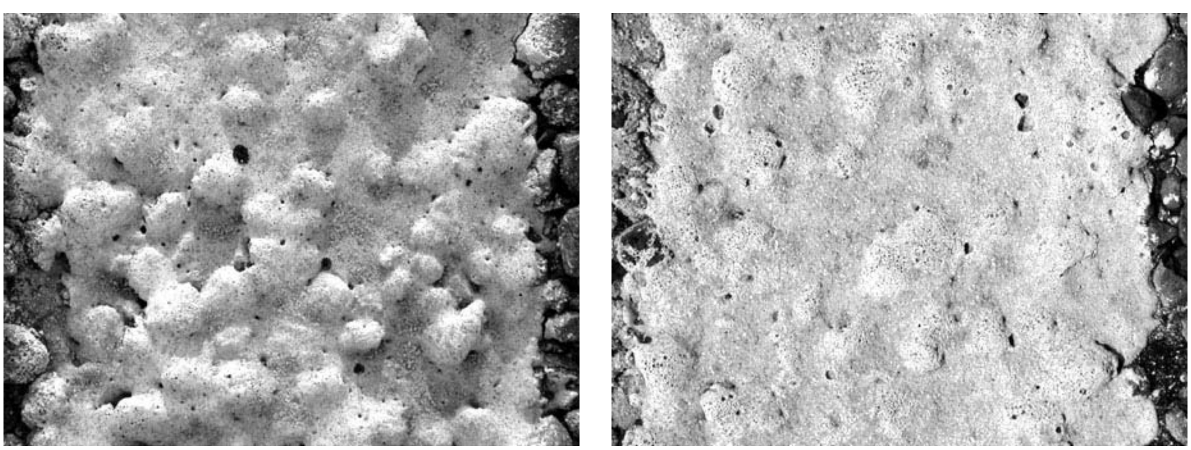


Figure 31. Confidence Intervals for Average Initial and 4-Month Retroreflectivity vs. Thermoplastic Thickness.

Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Sealcoat Aggregate Density

During the site visits, TTI research staff noted inconsistencies in the dispersion of aggregates laterally across the sealcoat surface. For example, sealcoat aggregates were more closely spaced near the center of the roadway when compared to the edge of the roadway, creating a smoother surface for striping. Figure 32 displays a comparison of a typical white thermoplastic edge line vs. lane line on the primed thermoplastic section of US 90.



a. Edge Line - Sparse Aggregate Coverage **b. Lane Line - Dense Aggregate Coverage**

Figure 32. Typical 100 mil White Thermoplastic Edge Line vs. Lane Line, US 90.

Figure 33 provides a comparison of the retroreflectivity data from the white thermoplastic edge line (sparse aggregate spacing) vs. lane line (dense aggregate spacing).

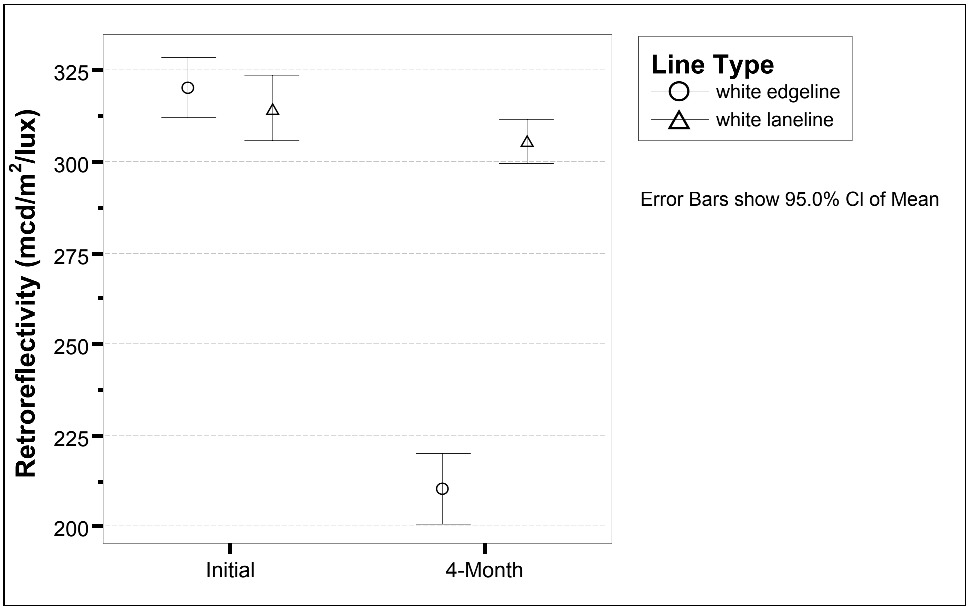


Figure 33. Confidence Intervals for Average Initial and 4-Month Retroreflectivity for Edge Line vs. Lane Line.

Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Figure 33 shows that while the initial retroreflectivity levels were nearly identical, the 4-month retroreflectivity was significantly better for the white lane line vs. the white edge line, indicating better bead retention over time. Because of the absence of shoulders on US 90, it was assumed that traffic wear was not likely any greater on the edge line than on the lane line. Therefore, it was concluded that creating a more tightly compacted sealcoat surface provides for better pavement marking retroreflectivity over time. This finding was similar to the findings of Evaluations #1 and #2 for thermoplastic on smoother surfaces (i.e., HMAC) vs. coarser surfaces (i.e., sealcoat).

Directional Retroreflectivity

Retroreflectivity data for the yellow centerline on FM 365 mostly showed slight differences as a function of measurement direction. Figure 34 displays the 95 percent confidence intervals for average yellow centerline retroreflectivity on FM 365 both initially and after four months as a function of measurement direction and material type.

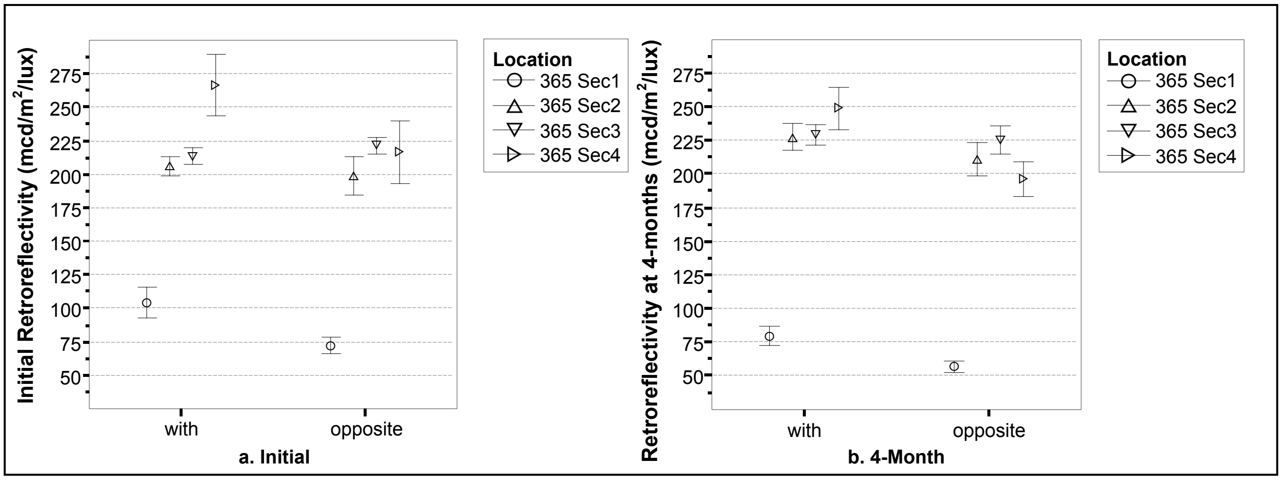


Figure 34. Confidence Intervals for Average Initial and 4-Month Retroreflectivity for Yellow Centerline.

Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

In nearly every case, yellow centerlines had slightly higher levels of retroreflectivity both initially and after four months when measured *with* the direction of the striping operation (frontside) vs. *opposite* the direction of striping operation (backside). However, these differences were statistically significant only for paint and thermoplastic with large glass beads. The differences in yellow centerline retroreflectivity as a function of measurement direction were far less pronounced in this experiment than in the thermoplastic thickness experiment (Evaluation #3).

Summary of Findings

Thermoplastic Performance

- All sections of thermoplastic displayed adequate retroreflectivity after four months:
  - average white: 200 to 400 mcd/m^2/lx
  - average yellow: 150 to 225 mcd/m^2/lx.
- Thermoplastic retroreflectivity was, in many cases, found to increase over the first four months.
- Double thermoplastic applications displayed slightly higher (but not statistically significant) retroreflectivity at four months when compared to single applications of similar thickness.

Waterbased Paint Performance

- White paint maintained reasonable levels of retroreflectivity after four months, averaging 170 – 230 mcd/m^2/lx.
- Nearly all yellow paint sections were approaching replacement levels after four months, averaging below 100 mcd/m^2/lx.

Waterbased Paint vs. Thermoplastic

- Waterbased paint pavement markings provided significantly lower levels of retroreflectivity than all thermoplastic applications both initially and after 4 months.
  - Initial retroreflectivity:
    - up to 150 mcd/m^2/lx less than thermoplastic.
  - Four-month retroreflectivity:
    - up to 225 mcd/m^2/lx less than thermoplastic.

Waterbased Paint as a Primer

- Thermoplastic applied over waterbased paint primer maintained slightly higher levels of retroreflectivity (but not statistically significant) vs. unprimed thermoplastic both initially and after four months.
- Use of waterbased paint primer under thermoplastic reduced considerably the occurrence of emulsified asphalt bleeding up through the thermoplastic when compared to unprimed thermoplastic sections.
  - Bleeding on the unprimed sections was not severe enough to significantly affect retroreflectivity. Nighttime visibility comparisons support this finding.

Sealcoat Characteristics

- Asphalt bleeding through the thermoplastic occurred more frequently if markings were placed near a longitudinal joint, such as the center joint or shoulder joint.
- Thermoplastic pavement markings placed on sections with densely spaced aggregates displayed better retroreflective performance over time vs. those placed on sections with sparsely spaced aggregates.

Glass Bead Performance

- No considerable differences in retroreflectivity were found between thermoplastic with large glass beads (TxDOT Type III) vs. small glass beads (TxDOT Type II).

Directional Retroreflectivity

- Yellow centerlines had slightly higher levels of retroreflectivity both initially and after four months when measured *with* the direction of the striping operation (frontside) vs. *opposite* the direction of striping operation (backside).

EVALUATION #5: EVALUATION OF GLASS BEAD SIZE AND SEALCOAT AGGREGATE GRADE

Over the past five years, TxDOT experienced an increase in both the use of large glass surface beads for striping and the use of larger aggregate for sealcoats. Many TxDOT personnel perceive large glass beads (now designated by TxDOT as Type III) as providing increased retroreflectivity over the smaller Type II glass beads that had been TxDOT's standard for many years. Although Evaluation #4 showed no considerable differences in retroreflectivity between 100 mil thermoplastic with large vs. small glass beads, further evaluation of glass bead size was deemed necessary.

Sealcoat aggregate size recently became an important issue as TxDOT districts have begun to specify Grade 3 aggregates, which are larger than the commonly used Grade 4 aggregates. The resulting Grade 3 sealcoats are often coarser than Grade 4 sealcoats, creating a more textured surface for pavement markings and possibly reducing retroreflective performance. Researchers decided that a formal field evaluation would be helpful to quantify differences in performance for thermoplastic on Grade 3 vs. Grade 4 sealcoat.

The objectives of this evaluation were as follows:

- determine the difference in retroreflective performance of large glass beads (TxDOT Type III) vs. small glass beads (TxDOT Type II) for 100 mil thermoplastic on new sealcoat and
- determine the difference in retroreflective performance of 100-mil thermoplastic placed on new Grade 3 sealcoat vs. new Grade 4 sealcoat.

Description of Evaluation

Table 25 displays the attributes of this evaluation.

Table 25. Attributes of Evaluation #5.

Locations	FM 2838, FM 1365, FM 2117, Loop 265, FM 1512 (all Waco District)
Roadway Types	Two-way, two-lane rural highway with shoulders
Average Daily Traffic	500 - 1500
Striping Date	First two weeks of September 2003
Thermoplastic Thickness	100 mil
Evaluation Period	1-month after striping
Striping Condition	New sealcoat surfaces
Experimental Variables	• Sealcoat Aggregate Grade 1. Grade 3 (Larger) 2. Grade 4 (Smaller) • Bead Size 1. TxDOT Type II (Small) 2. TxDOT Type III (Large) • Centerline Pattern 1. Skip 2. Solid • Centerline Measurement Direction 1. With Direction of Striping (Frontside) 2. Opposite Direction of Striping (Backside)
Measure of Effectiveness	• Retroreflectivity after one month

The striping sections on each the five roadways were between 2 and 5 miles in length. Unlike other evaluations that have been described in this report, each roadway received a single marking treatment over the entire length. TTI researchers were not present during the striping operation, and no initial retroreflectivity measurements were taken. Table 26 displays the characteristics of each striping treatment section.

Table 26. Characteristics of Striping Treatment Sections.

	FM 2838	FM 1365	FM 2117	LP 265	FM 1512
Thermoplastic Thickness (mil)	100	100	100	100	100
Sealcoat Aggregate (TxDOT)	Grade 4	Grade 4	Grade 4	Grade 4	Grade 3
Glass Bead (TxDOT)	Type III	Type III	Type II	Type II	Type III
Length of Striping Section	3 miles	6 miles	5 miles	2 miles	4 miles
Number of Evaluation Checkpoints Per Roadway	2 white, 2 yellow	2 white, 2 yellow	2 white, 2 yellow	2 white, 2 yellow	2 white, 2 yellow
Number of Retroreflectivity Measurements Per Roadway	80 white, 80 yellow	80 white, 80 yellow	80 white, 80 yellow	80 white, 80 yellow	80 white, 160 yellow

Site Visit

Field evaluation of each striping section measured characteristics after the markings had been in place for approximately one month. Two pavement marking evaluation checkpoint areas were defined within each treatment section. Checkpoint locations randomly chosen at either end of each section provided a representative sample for a given treatment. Twenty retroreflectivity measurements were taken on each line-type within a given checkpoint area. White edge line retroreflectivity was measured only in the direction of traffic, while yellow centerlines were measured in both directions.

Every checkpoint included a section of passing/no passing zone with skip and solid yellow markings side-by-side. Both skip and solid yellow centerlines were measured side-by-side in both directions, with 10 measurements per direction per line type.

Analysis

To determine the effect of the various glass bead/sealcoat aggregate combinations on retroreflectivity, many separate analyses were performed.

- The *1-month retroreflectivity* was analyzed as a function of the glass bead type and marking color.
- The *1-month retroreflectivity* was analyzed as a function of the sealcoat aggregate grade and marking color.
- The *1-month retroreflectivity* for yellow centerline markings was analyzed as a function measurement direction and marking pattern (skip vs. solid).

Effect of Glass Bead Type and Sealcoat Aggregate Grade

Table 27 displays the average 1-month retroreflectivity for white and yellow markings at each site.

Table 27. Average 1-Month Retroreflectivity for 100 mil Thermoplastic.

	Retroreflectivity (mcd/m²/lx)				
	Type III Beads on Grade 4		Type II Beads on Grade 4		Type III Beads on Grade 3
	FM 2838	FM 1365	FM 2117	LP 265	FM 1512
White Edge Lines	345	338	275	376	287
Solid Yellow Centerlines – Frontside	143	152	137	122	116
Solid Yellow Centerlines – Backside	90	106	80	81	79
Skip Yellow Centerlines – Frontside	306	192	164	142	141
Skip Yellow Centerlines - Backside	238	154	96	106	86

Statistical analysis showed that the glass bead type, sealcoat aggregate grade, and marking color all had a statistically significant effect on retroreflectivity after one month. Figure 35 displays the 95 percent confidence intervals for average 1-month retroreflectivity as a function of the glass bead type, sealcoat aggregate grade, and color. Please note that the bead type comparison included only markings on Grade 4 sealcoat, and the sealcoat aggregate comparison included only markings with Type III beads.

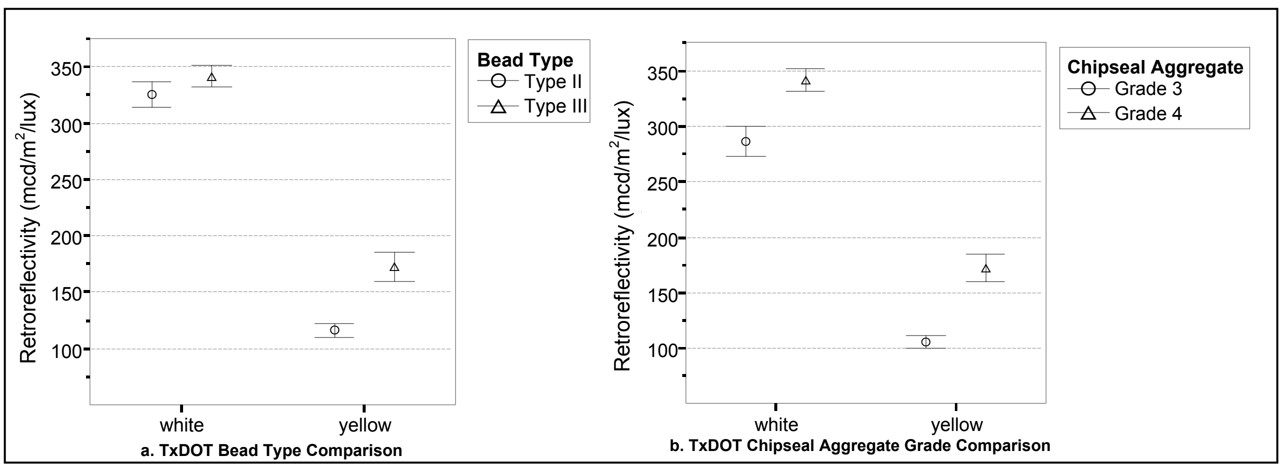


Figure 35. Confidence Intervals for Average 1-Month Retroreflectivity.
Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Figure 35a shows that Type III beads provided higher levels of retroreflectivity for both white and yellow 100 mil thermoplastic markings on Grade 4 sealcoat, although the difference was statistically significant for yellow markings only. Markings with Type III beads had retroreflectivity levels after one month that were on average, 20 mcd/m²/lx and 55 mcd/m²/lx higher vs. markings with Type II beads for white and yellow, respectively.

Figure 35b shows that Grade 4 sealcoat (smaller aggregate) provided significantly higher levels of retroreflectivity vs. Grade 3 sealcoat (larger aggregate) for 100 mil thermoplastic with Type III beads. The magnitude of this difference was, on average, 55 mcd/m^2/lx and 70 mcd/m^2/lx for white and yellow, respectively.

Effect of Marking Pattern and Measurement Direction for Yellow Centerlines

Further analysis on the yellow centerline markings on the Grade 4 sealcoats showed that the measurement direction, marking pattern, and glass bead type, all had a statistically significant effect on retroreflectivity after one month. Figure 36 displays the 95 percent confidence intervals for average 1-month retroreflectivity of yellow centerlines as a function of measurement direction, marking pattern, and glass bead type.

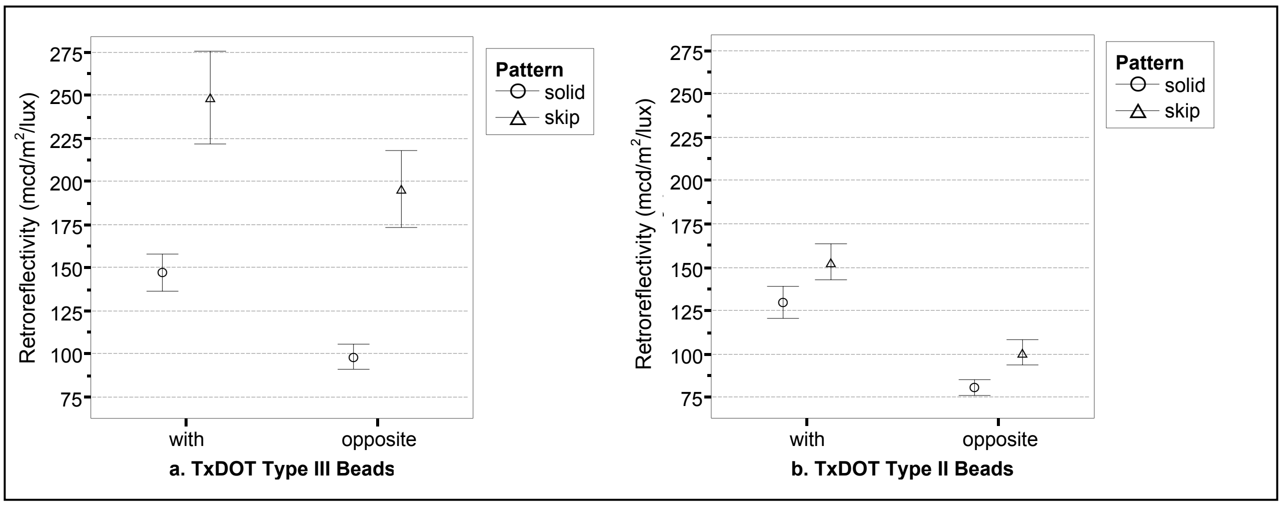


Figure 36. Confidence Intervals for Average 1-Month Yellow Centerline Retroreflectivity.
Figure Note: Overlapping confidence intervals indicate no statistical difference between the populations.

Figure 36 shows that in every case, skip centerlines provided significantly higher levels of retroreflectivity when compared to solid centerlines. These differences were much more pronounced when Type III beads were used. During the site visit, TTI researchers noted that the skip centerline always appeared to be slightly thicker and with better bead dispersion than its solid counterpart. A typical skip/solid centerline combination is shown in Figures 37 and 38. Note the thicker appearance of the skip centerline (left) vs. the solid centerline (right).

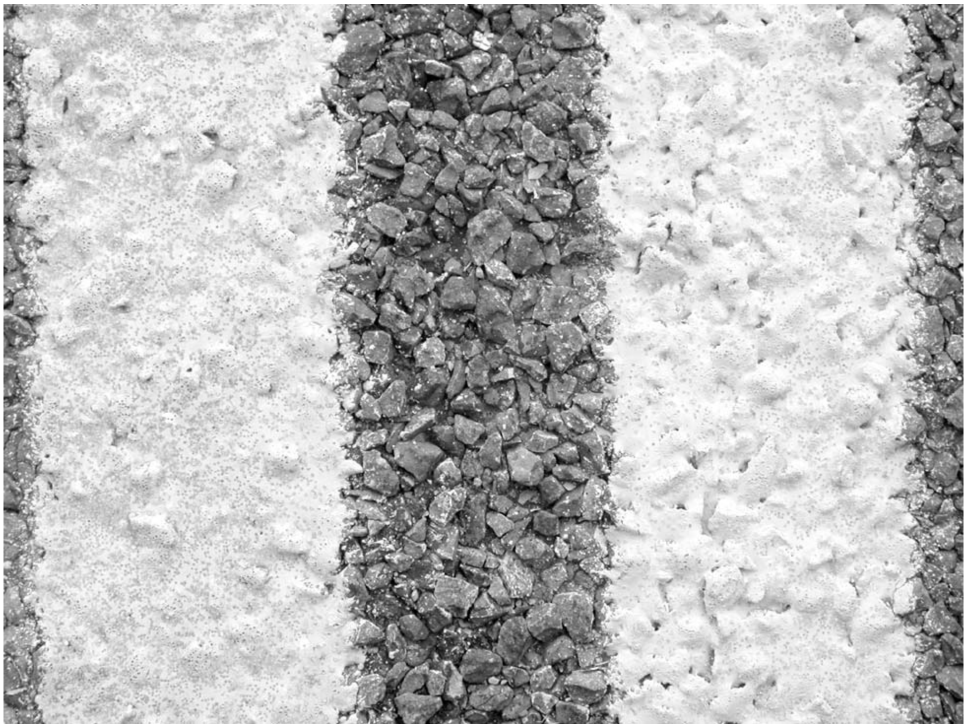
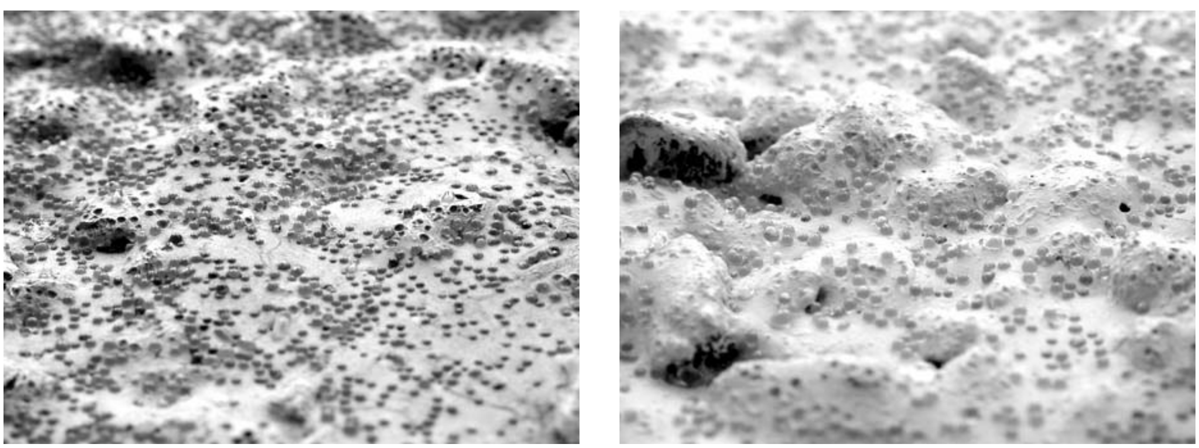


Figure 37. Typical Skip (left)/Solid (right) Centerline on Grade 4 Sealcoat.



a. Skip Centerline **b. Solid Centerline**

Figure 38. Close-Up Skip/Solid Centerline on Grade 4 Sealcoat.

A contractor explanation for this phenomenon is that the thermoplastic striping truck cannot supply the necessary quantities of striping material to produce two 100 mil stripes simultaneously. Therefore, one of the two stripes consistently receives less material. For this evaluation, the skip centerlines always appeared to receive greater material quantities compared to the solid centerline.

Similar to the findings from other field evaluations cited in this report, for all cases, yellow centerline retroreflectivity measured *with* the direction of the striping operation was significantly higher than retroreflectivity measurements taken in the *opposite* direction of the striping operation. Again, this indicates that the frontsides of the aggregates received better bead/binder coverage than the backsides.

Summary of Findings

Effect of Glass Bead Size

- Type III beads provided higher levels of thermoplastic retroreflectivity vs. Type II beads:
  - average white edge line: 20 mcd/m^2/lx higher with Type III beads vs. Type II and
  - average yellow centerline: 55 mcd/m^2/lx higher with Type III beads vs. Type II.
- Retroreflectivity differences were only statistically significant for yellow markings.

Effect of Chipseal Aggregate Size

- Grade 4 sealcoat provided significantly higher levels of thermoplastic retroreflectivity vs. Grade 3 sealcoat:
  - average white edge line: 55 mcd/m^2/lx higher for Grade 4 vs. Grade 3 and
  - average yellow centerline: 70 mcd/m^2/lx higher for Grade 4 vs. Grade 3.

Application of Double Centerlines

- Thermoplastic double centerlines (solid/solid line or solid/broken line) were applied inconsistently due to limitations in the capabilities of the striping truck:
  - One of the two lines was consistently thinner and had fewer glass beads than the other, causing significant differences in retroreflectivity.
  - Retroreflectivity differences were much more pronounced with Type III beads.

Directional Retroreflectivity for Yellow Centerlines

- Similar to the findings from other field evaluations cited in this report, yellow centerline retroreflectivity measured *with* the direction of the striping operation was significantly higher than retroreflectivity measurements taken *opposite* the direction of the striping operation.

CHAPTER 5:
THERMOPLASTIC SERVICE LIFE ESTIMATION

A major component of the research was to determine retroreflectivity-based service lives for thermoplastic pavement markings. To accomplish this task, the researchers monitored retroreflectivity over a two-year period for 47 thermoplastic longitudinal pavement markings on nine TxDOT highways in the Bryan-College Station area. Data were then analyzed, with the results reported later in this chapter.

SITE CHARACTERISTICS

Sites were selected to provide a representative sample of TxDOT pavement surfaces and traffic volumes. Sites with very high traffic volumes were not included because of worker-safety issues involved with retroreflectivity measurement. Site characteristics are listed in Table 28.

Table 28. Site Characteristics for Thermoplastic Retroreflectivity Monitoring.

Highway	Lanes	ADT	Pavement Surface	Marking Colors	Number of Site Visits	Age of Markings at Final Site Visit (months)	Number of Retro Models Per Site
US 79	2	3100	Sealcoat (Gr 4)	W, Y	4	8.4	11
FM 159	2	300	Sealcoat (Gr 4)	W, Y	11	22.0	4
FM 974	2	800	Sealcoat (Gr 4)	W, Y	15	21.9	4
FM 2818	2	3900	Sealcoat (Gr 4)	W, Y	2	7.7	4
FM 1179	5	19,500	HMAC	W, Y	11	22.0	3
FM 2347 East	5	22,000	HMAC	W, Y	22	20.6	8
FM 2347 West*	4	18,500	PCC	W	8	18.1	3
SH 47*	4	10,000	HMAC, PCC	W	2	7.8	8
FM 2154	3	6800	HMAC	Y	7	17.6	2

Legend: W = white, Y = yellow
* Divided Roadway

On all HMAC and sealcoat roadways, thermoplastic markings were applied to new virgin pavement. However, due to the lack of new PCC pavement construction, existing PCC pavement surfaces were used, and thermoplastic was placed over the existing thermoplastic markings. Striping at the sites occurred between June 2001 and August 2002. All markings were sprayed thermoplastic long-lines applied at widths of 4 to 8 inches and thicknesses between

60 and 110 mils. The markings were applied by a variety of contractors using TxDOT standard thermoplastic materials (DMS 8220) and either Type II or Type III glass surface beads.

At a minimum, the markings were measured both initially and at least 7 months after striping, although most sites were visited on numerous occasions. TTI researchers made all retroreflectivity measurements using the same 30-meter geometry handheld retroreflectometer. In total, approximately 5900 retroreflectivity measurements were made over a two-year period.

METHODOLOGY FOR SERVICE LIFE ESTIMATION

The objective of the analysis was to determine, based on the data collected at these sites, reasonable expectations for thermoplastic service life as a function of pavement surface and marking color.

General Modeling Description

Researchers used statistical modeling of the retroreflectivity data vs. time to estimate service lives of the markings. Large variations in the retroreflectivity data existed from site-to-site and line-to-line. As a result, models were developed for each line at each site with two separate models created for each yellow centerline based on measurement direction. Approximately 5900 retroreflectivity measurements made at the nine sites generated 47 retroreflectivity models. The modeling procedures were similar to those used by Migletz, et al. in a pavement marking service-life study for FHWA (*15*).

Threshold Retroreflectivity Level

No criteria currently exist for establishing retroreflectivity levels that define the end-of-service-life for pavement markings. However, based on suggestions from numerous literature sources (*6,7,8*) and FHWA retroreflectivity guidelines (*13*), the researchers selected 100 mcd/m^2/lx for the retroreflectivity service-life threshold for all markings included in this analysis. Therefore, the service life for an individual marking was defined as the amount of time between marking placement and when marking retroreflectivity had degraded to 100 mcd/m^2/lx based on the regression model. Please note that the 100 mcd/m^2/lx retroreflectivity threshold was selected for analysis purposes only and does not constitute a standard or establish a minimum level.

Maximum Thermoplastic Service Life

In many cases, retroreflectivity was found to increase over the life of the marking, causing subsequent service life estimations to approach infinity. In these cases, it was necessary to assign an assumed maximum service life value. The FHWA service-life study by Migletz et al. (*15*) and observations by TxDOT personnel suggested four years as a reasonable maximum service life for thermoplastic. Therefore, for the analyses performed here, the researchers assumed a maximum thermoplastic service life of four years.

Retroreflectivity Modeling Procedures

Two modeling approaches were used to determine service lives of the markings:

- Modeling Approach #1: Linear, exponential, and logarithmic regression models have been shown in previous research to provide a good representation of changes in pavement marking retroreflectivity over time (*15*). The first, and preferred, method for quantifying retroreflectivity vs. time was by fitting linear, exponential, and logarithmic regression models to the data for each pavement marking at each site. The model with the highest R^2 was generally selected as the preferred model for that line, assuming that the model was significant (based on the F-statistic) and R^2 was greater than 0.15. For pavement markings that were measured only on two occasions, only linear regression was performed.
- Modeling Approach #2: For cases where none of the regression models were significant or all R^2 were less than 0.15, a more primitive modeling approach was considered in which a straight line was passed through the average initial and average final retroreflectivity measurements. The slope and intercept of this line determined a linear model.

RESULTS

A total of 47 models were generated, which accounted for all measured lines at all sites. For yellow centerlines, separate models were generated for each retroreflectivity measurement direction (with the direction of striping vs. opposite the direction of striping). The outcome of the modeling procedure was as follows:

- 14 linear regression (30 percent),
- 10 logarithmic regression (21 percent),
- 6 exponential regression (13 percent), and
- 17 cases in which no model could be fit to the data (36 percent) and therefore Modeling Approach #2 (endpoint model) was employed.

The R^2 values for the regression models were summarized as follows:

- Average: 0.52
- 25th percentile: 0.39
- 75th percentile: 0.70

Predicted Retroreflectivity Performance

Figures 39 – 41 display the results of the retroreflectivity modeling procedures for *white* thermoplastic on HMAC, PCC and sealcoat, respectively. Similar results were found for yellow markings, which can be found in Appendix B. Complete results of the modeling procedures and service life estimations can also be found in Appendix B.

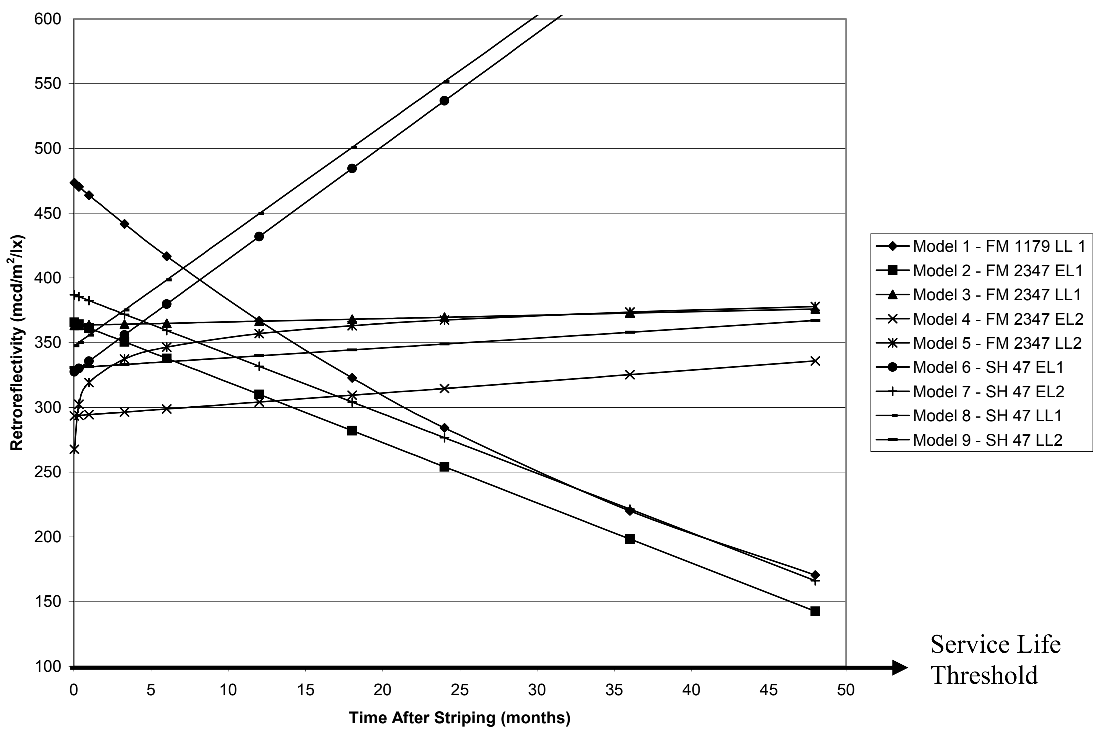


Figure 39. Retroreflectivity Modeling for White Thermoplastic on HMAC.

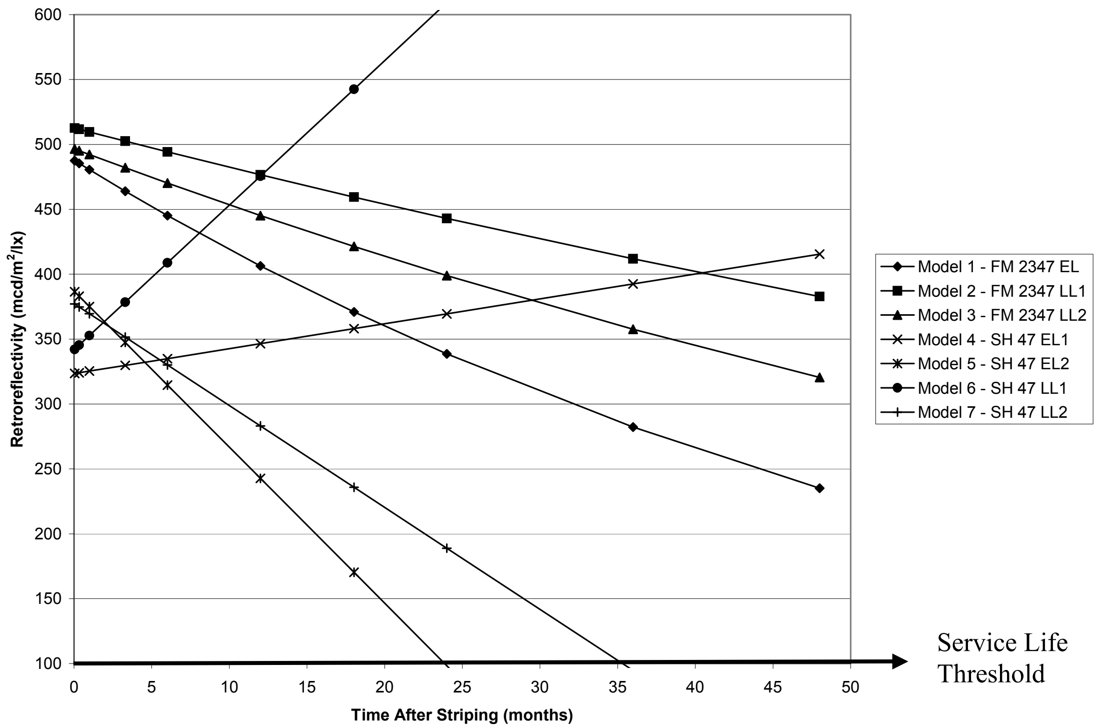


Figure 40. Retroreflectivity Modeling for White Thermoplastic on PCC.

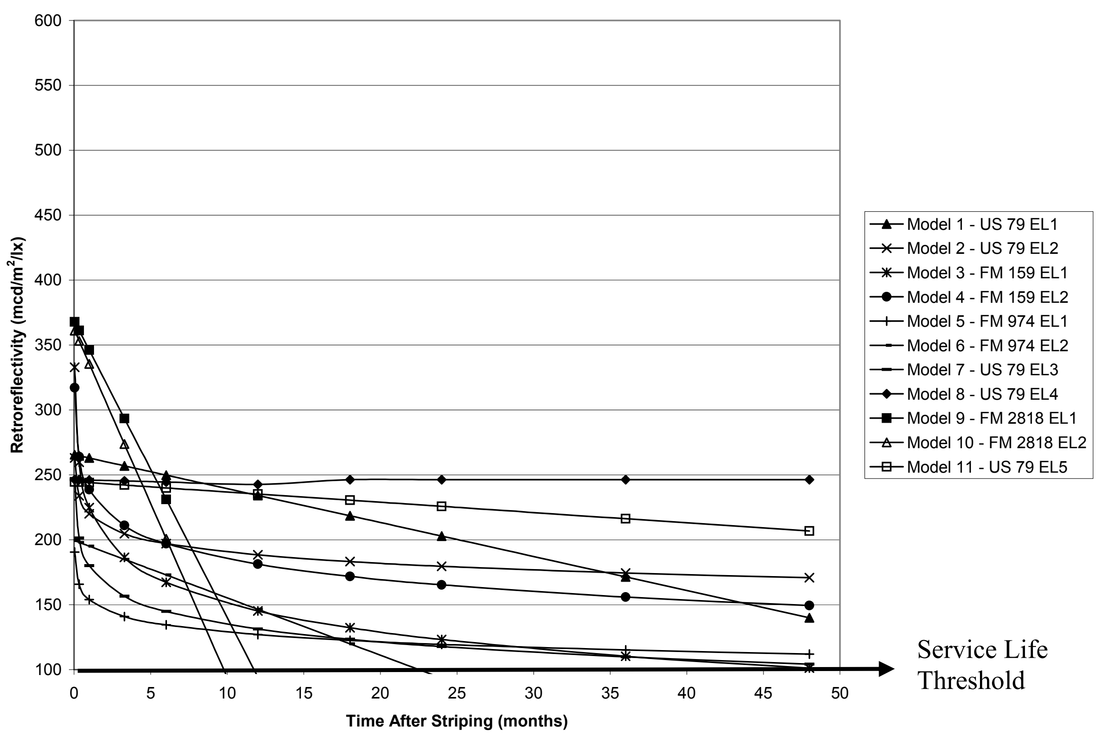


Figure 41. Retroreflectivity Modeling for White Thermoplastic on Sealcoat.

Service Life Estimation

The regression coefficients from each of the models were used to estimate the service life for the corresponding pavement marking using the 100 mcd/m^2/lx end-of-service-life threshold. Four years was assumed as the maximum service life that could reasonably be expected for thermoplastic in Texas. The estimated service life values were then averaged for all markings of a given pavement surface type and marking color. Table 29 presents the results of the service life estimations based on pavement surface type and marking color.

Table 29. Estimated Thermoplastic Service Life Based on Pavement Surface and Color.

Color	Pavement Surface	Average Service Life (years)	Service Life Range (years)	Number of Sites Analyzed	Number of Markings Analyzed	Total Number of Retroreflectivity Measurements	Markings Displaying an Increase from Initial to Final Retro. Measurement (percent)
White	HMAC	4.0	4.0	3	9	839	56
	Sealcoat	3.2	0.8 – 4.0	4	11	1834	0
	PCC	3.6	2.0 – 4.0	2	7	608	29
Yellow	HMAC	3.9	3.7 – 4.0	3	8	1178	63
	Sealcoat	2.9	0.7 – 4.0	4	12	1440	17

Note: With the exception of PCC, all pavement surfaces were new and previously unmarked. For PCC surfaces, thermoplastic was striped over existing thermoplastic.

As expected, HMAC roadways provided longer average service lives for thermoplastic than sealcoat or PCC pavement surfaces. Thermoplastic markings on HMAC were also much more likely to display increases in retroreflectivity over time than thermoplastic markings on sealcoat and PCC pavements. In addition, white markings were found to slightly outperform their yellow counterparts.

SUMMARY OF FINDINGS

The statistical modeling procedures for retroreflectivity of Texas thermoplastic resulted in a number of findings, which are listed here. Please note that service life estimations were based on measurements at a limited number of sites and may not be representative of the service life of markings at all locations.

Estimated Service Life

- Based on an end-of-service-life retroreflectivity threshold of 100 mcd/m^2/lx and a maximum service life of four years, average thermoplastic service lives for new pavement surfaces[5] were estimated as follows:
  - HMAC: 4.0 years (white), 3.9 years (yellow),
  - Sealcoat: 3.2 years (white), 2.9 years (yellow), and
  - PCC: 3.6 years (white).

Long-Term Retroreflectivity Performance

- Approximately half of the thermoplastic markings on HMAC experienced long-term retroreflectivity increases.
- Most of the thermoplastic markings on sealcoat or PCC experienced long-term retroreflectivity decreases.

Service Life Variability

- Thermoplastic service life estimates are highly variable even for similar materials on similar pavements. As a result, separate models were generated for each individual pavement marking.
- Variability in service life data may be attributed to: variability in traffic levels, quality of contractor installation, environmental conditions, glass beads gradations, material manufacturers, thermoplastic application thicknesses, quality control, and other factors.

[5] Thermoplastic markings on PCC pavements were restriped over existing thermoplastic.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The research described within this report focused upon identifying pavement marking problems on sealcoat and HMAC surfaces, the causes of these problems, and a determination of feasible potential solutions. Activities that identified major issues included: a literature review, a survey of TxDOT districts, preliminary field investigations, and meetings with stakeholders. The researchers then addressed these issues through field evaluations of various pavement marking applications. The evaluations included:

- performance of thermoplastic on sealcoat vs. hot-mix asphalt,
- effect of thermoplastic thickness on performance,
- performance of large vs. small glass beads for thermoplastic,
- effect of sealcoat aggregate size on thermoplastic performance,
- expected service life of thermoplastic markings on various pavement surfaces,
- performance of waterbased paint as permanent marking on new sealcoat,
- effect of waterbased paint as a primer prior to thermoplastic on new sealcoat, and
- effect of double application for thermoplastic.

In most of these field evaluations, researchers measured the retroreflectivity of newly applied pavement markings and monitored the performance of the markings over time. In total, researchers made over 9000 retroreflectivity measurements at 18 different sites.

CONCLUSIONS

Based on the results of the field evaluations, the researchers identified few shortcomings related to pavement marking practices on HMAC pavement surfaces. However, for sealcoat pavement surfaces, numerous opportunities for improving pavement marking quality were identified. Consequently, the conclusions presented primarily address pavement markings on sealcoats.

Thermoplastic Performance on Sealcoat vs. HMAC

- On new sealcoat, thermoplastic applied at a minimum of 90 mil (to top of binder) generally provides the best retroreflective performance over time.
- On new HMAC, thermoplastic applied between 60 and 90 mil generally provides the best retroreflective performance over time.
- Thermoplastic performance is usually poorer on sealcoat than HMAC, largely due to greater pavement surface texture for sealcoat:
  - Thermoplastic markings on sealcoat often possess lower levels of retroreflectivity both initially and over time compared to the same markings on HMAC.
  - Thermoplastic pavement markings on sealcoat lose retroreflectivity more rapidly over time than thermoplastic markings on HMAC.
  - Sealcoat markings often have higher retroreflective variability when compared to HMAC markings.
  - Thermoplastic retroreflectivity is much more likely to increase over time on HMAC vs. sealcoat.
- Sealcoat with smaller aggregate (TxDOT Grade 4) provides significantly higher levels of retroreflectivity vs. sealcoat with larger aggregate (TxDOT Grade 3) for 100 mil thermoplastic.

Thermoplastic Application Techniques

- Double application of thermoplastic on new sealcoat surface (each application applied at approximately half the final thickness) provides only slightly higher retroreflectivity over time when compared to single thermoplastic application.
- Asphalt bleeding through thermoplastic occurs more frequently if markings are placed where asphalt binder is applied thicker, such as near the center joint or shoulder joint.
- Thermoplastic pavement markings placed on sealcoat with densely spaced aggregates display better retroreflective performance vs. thermoplastic placed on sealcoat with sparsely spaced aggregates.

  - Sparse aggregate spacings are common near the edge of the pavement, which may affect edge line durability on roads without shoulders.
- Thermoplastic double centerlines (solid/solid line or solid/broken line) are often applied inconsistently due to limitations in striping truck capabilities. As a result, one of the two lines is often thinner and has fewer glass beads than the other, which may affect retroreflectivity.

Thermoplastic Service Life Estimation

- Based on an end-of-service-life retroreflectivity threshold of 100 mcd/m^2/lx, the research evaluations estimate the average thermoplastic service lives for new pavement surfaces[6] at the following values:
  - HMAC: 4.0 years (white), 3.9 years (yellow),
  - Sealcoat: 3.2 years (white), 2.9 years (yellow), and
  - PCC: 3.6 years (white).
- Thermoplastic service life estimates are highly variable even for similar materials on similar pavements. The research evaluations of service life were based on measurements at a limited number of sites and may not be representative of the service life of markings at all locations.
  - Variability in service life data may be attributed to: variability in traffic levels, quality of contractor installation, environmental conditions, glass beads gradations, material manufacturers, thermoplastic application thicknesses, quality control, and other factors.

General Retroreflectivity Observations

- Although thermoplastic retroreflectivity generally degrades over the long term, retroreflectivity may increase over the first few months as excess surface beads wear away.
- Thermoplastic retroreflectivity changes rapidly in the first month after striping, usually stabilizing somewhat after one month. As a result, retroreflectivity

[6] Thermoplastic markings on PCC pavements were restriped over existing thermoplastic.

measurements taken within the first month after striping may not be representative of the long-term retroreflective performance of markings.

- Heavy rain often has a significant cleaning effect on dirty thermoplastic markings, consequently improving retroreflectivity.

Directional Retroreflectivity for Centerlines

- Regardless of marking material, retroreflectivity measurements made *with* the direction of the striping operation (frontside) are usually higher than those made *opposite* the direction of striping (backside).
- Differences in directional retroreflectivity indicate differences in bead/binder coverage on opposite sides of the aggregate.
- Directional retroreflectivity differences are a greater problem on sealcoat than HMAC due to the greater surface texture for sealcoat.
- Thermoplastic markings that are thinner than 100 mil on sealcoat are especially susceptible to differences in directional retroreflectivity.

Glass Beads for Thermoplastic

- For thermoplastic, no consistent or considerable differences in dry-weather retroreflective performance exist between larger diameter glass surface beads (TxDOT Type III) vs. smaller diameter glass surface beads (TxDOT Type II).
- Although not evaluated in the research performed here, it is widely accepted that large surface beads provide a wet-weather visibility benefit when compared to small surface beads.

Waterbased Paint Pavement Markings on New Sealcoat

- Waterbased paint used as a permanent marking on a new sealcoat provides significantly lower levels of retroreflectivity than thermoplastic both initially and over time.
- White paint generally maintains acceptable levels of retroreflectivity over time.
- Yellow paint often drops below 100 mcd/m^2/lx during the first few months after application.

Waterbased Paint Primer on New Sealcoat

- New sealcoat primed with waterbased paint prior to thermoplastic application provides only slightly higher levels of retroreflectivity for the thermoplastic vs. unprimed sealcoat.
- Priming new sealcoat with paint prior to thermoplastic application reduces the occurrence of asphalt bleeding through the thermoplastic when compared to unprimed sealcoat. However, the bleeding on the unprimed sealcoat is generally not severe enough to significantly affect retroreflectivity.

RECOMMENDATIONS

Based on the research findings, the researchers developed the following list of recommendations for TxDOT to consider.

Thermoplastic Pavement Markings on Sealcoat

- Apply thermoplastic at a *minimum* thickness of 100 mil for all longitudinal pavement markings on new sealcoat when no other durable marking exists.
- Thinner applications may be used for restripe, but should not be less than 60 mil.
- Double applications of thermoplastic may be used to achieve necessary thickness on coarse sealcoats. However, the retroreflectivity benefits of double applications are marginal, and there may be retracing challenges that reduce the overall effectiveness of the marking.
- Thermoplastic should not be placed directly on longitudinal sealcoat joints.

Thermoplastic Pavement Markings on HMAC

- Apply thermoplastic at a *maximum* thickness of 90 mil for all longitudinal pavement markings on HMAC when no other durable marking exists.
- Thinner applications may be used for restripe, but should not be less than 60 mil.

Waterbased Paint Pavement Markings on Sealcoat

- Do not use waterbased paint as permanent pavement marking on new sealcoat surfaces.

- Waterbased paint may be used on a new sealcoat surface in either of the following situations:
  - as temporary pavement marking for up to six months, or
  - as surface primer prior to thermoplastic application.

Sealcoat Aggregate

- For better retroreflective performance of pavement markings on sealcoat, TxDOT Grade 4 sealcoat aggregate (smaller diameter) is recommended over TxDOT Grade 3 sealcoat aggregate (larger diameter).
- Increasing the density of sealcoat aggregates per unit of surface area near the roadway edge will likely provide better retroreflective performance for edge line pavement markings on roadways without shoulders.

Glass Beads

- For any pavement surface, use either TxDOT Type III (larger diameter) or TxDOT Type II (smaller diameter) glass surface beads with thermoplastic to achieve suitable levels of dry-weather retroreflective performance.

Field Inspection

- To obtain an accurate representation of long-term pavement marking performance, measure retroreflectivity at least one month after striping.
- To ensure adequate retroreflectivity for both directions of traffic, measure retroreflectivity for centerlines of undivided two-way roadways in both directions.
- Application of double centerlines should be closely inspected to ensure that both lines are receiving adequate applications of material (binder and beads).

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APPENDIX A:
TXDOT DISTRICT SURVEY

To better understand TxDOT district practices regarding pavement marking on sealcoat roadways, a survey was developed by TTI and sent to traffic and maintenance personnel at all 25 TxDOT districts. The survey was sent via email from TxDOT's Traffic Operations office to district traffic and maintenance personnel in December 2000. Responses were received from 22 of the 25 districts by February 2001. The survey questionnaire is shown below.

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1. What type of marking material do you currently install on a new sealcoat?

    [ ] Thermoplastic
    [ ] Waterbased Paint as Primer and Thermoplastic
    [ ] Other:

2. If you put thermoplastic on a new sealcoat, what thickness is typically applied?

3. How much cure time do you require before the placement of any type of standard pavement markings?

4. If you put waterbased paint on a new sealcoat, how long do you wait before applying thermoplastic?

5. Does your district use a retroreflectivity specification for new markings? If so, what are the minimum retroreflectivity measurements for both white and yellow and when are measurements taken?

    [ ] Yes; white min.= yellow min.=

    When are measurements taken?

    How did you determine what these numbers should be and when the readings should be taken?

    [ ] No

6. What size rock does your district typically use for sealcoat? Does rock size affect the specified thickness of markings?

7. Please comment on any problems your district has had with markings on new sealcoat:

APPENDIX B:
RETROREFLECTIVITY MODELING

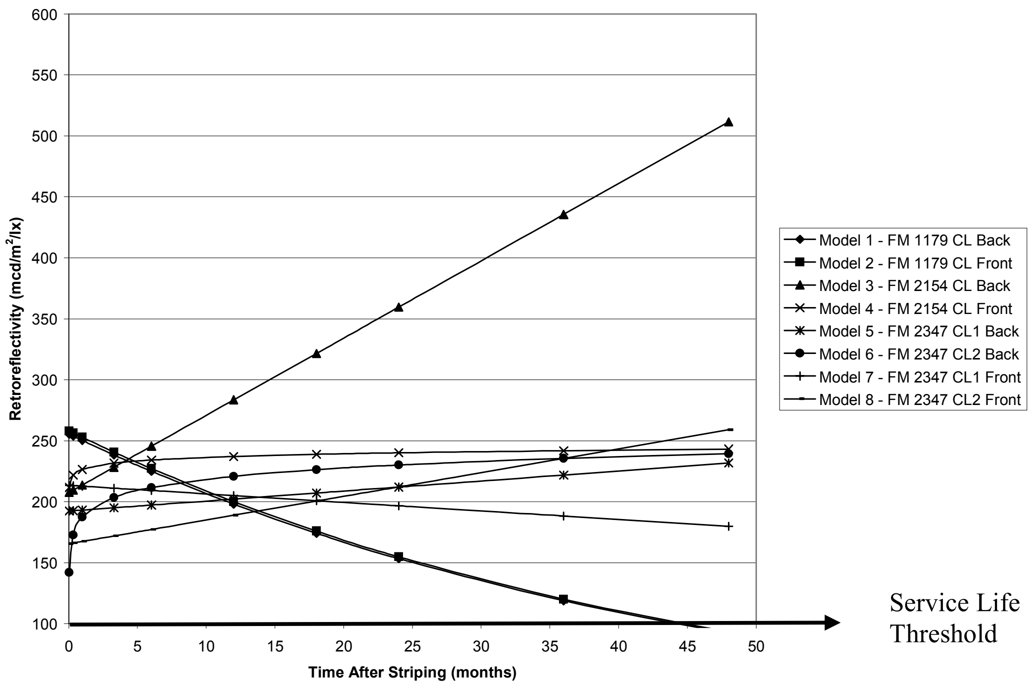

Figure B1. Retroreflectivity Modeling for Yellow Thermoplastic on HMAC.

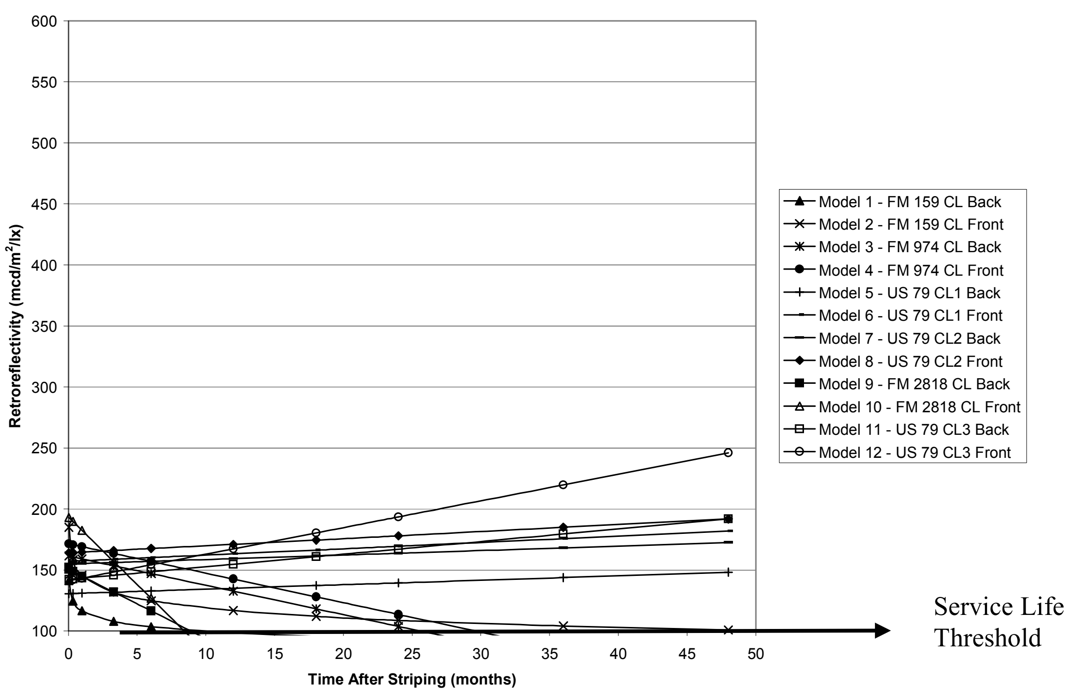

Figure B2. Retroreflectivity Modeling for Yellow Thermoplastic on Sealcoat.

Table B1. Retroreflectivity Modeling and Service Life Prediction.

Model Number	Roadway	Line	Direction	Age at Final Measurement (months)	# of Data Points for Model	Type of Model	R sq.	Model Coefficients		Predicted Service Life
								b0	b1	
White Thermoplastic - HMAC										
Model 1	FM 1179	LL	EB	22.0	220	Exponential	0.545	473.714	-0.0007	4.0
Model 2	Geo. Bush	EL1	EB	20.5	40	Endpoint	N/A	365.86	-0.153	4.0
Model 3	Geo. Bush	LL1	EB	20.5	30	Endpoint	N/A	363.35	0.0087	4.0
Model 4	Geo. Bush	EL2	WB	20.5	40	Endpoint	N/A	293.46	0.029	4.0
Model 5	Geo. Bush	LL2	WB	20.5	329	Log	0.381	267.617	15.143	4.0
Model 6	SH 47	EL1	NB	7.8	54	Linear	0.591	327.175	0.2871	4.0
Model 7	SH 47	EL2	SB	7.8	53	Linear	0.292	387.047	-0.1513	4.0
Model 8	SH 47	LL1	NB	7.8	36	Linear	0.519	347.3	0.28	4.0
Model 9	SH 47	LL2	SB	7.8	37	Endpoint	N/A	330.625	0.025	4.0
					Average Predicted Service Life =					**4.0**
White Thermoplastic - Sealcoat										
Model 1	US 79	EL1	EB	8.4	80	Endpoint	N/A	265.602	-0.086	4.0
Model 2	US 79	EL2	EB	8.4	160	Log	0.431	263.01	-12.648	4.0
Model 3	FM 159	EL1	EB	22.0	220	Log	0.854	332.951	-31.807	4.0
Model 4	FM 159	EL2	WB	22.0	220	Log	0.806	317.103	-23.02	4.0
Model 5	FM 974	EL1	EB	21.9	360	Log	0.452	190.585	-10.778	4.0
Model 6	FM 974	EL2	WB	21.9	360	Linear	0.386	199.547	-0.1454	1.9
Model 7	US 79	EL3	EB	8.4	157	Log	0.765	246.302	-19.489	4.0
Model 8	US 79	EL4	EB	8.4	40	Endpoint	N/A	246.38	-0.01	4.0
Model 9	FM 2818	EL1	EB	7.7	77	Linear	0.841	368.697	-0.7516	1.0
Model 10	FM 2818	EL2	WB	7.7	80	Linear	0.932	361.968	-0.8812	0.8
Model 11	US 79	EL5	EB	8.4	80	Endpoint	N/A	244.78	-0.026	4.0
					Average Predicted Service Life =					**3.2**
White Thermoplastic - PCC										
Model 1	Geo. Bush	EL	WB	18.1	139	Exponential	0.434	487.834	-0.0005	4.0
Model 2	Geo. Bush	LL1	EB	18.1	159	Exponential	0.17	512.666	-0.0002	4.0
Model 3	Geo. Bush	LL2	WB	18.1	132	Exponential	0.448	496.676	-0.0003	4.0
Model 4	SH 47	EL1	NB	7.8	56	Endpoint	N/A	323.446	0.0631	4.0
Model 5	SH 47	EL2	SB	7.8	56	Linear	0.696	386.929	-0.3953	2.0
Model 6	SH 47	LL1	NB	7.8	32	Linear	0.731	341.752	0.3666	4.0
Model 7	SH 47	LL2	SB	7.8	34	Linear	0.494	377.342	-0.2581	2.9
					Average Predicted Service Life =					**3.6**
Yellow Thermoplastic - HMAC										
Model 1	FM 1179	CL	Backside	22.0	220	Exp	0.482	255.626	-0.0007	3.7
Model 2	FM 1179	CL	Frontside	22.0	220	Exp	0.386	258.257	-0.0007	3.7
Model 3	FM 2154	CL	Backside	17.6	80	Linear	0.592	207.502	0.2083	4.0
Model 4	FM 2154	CL	Frontside	17.6	80	Log	0.208	211.768	4.3	4.0
Model 5	Geo. Bush	CL1	Backside	20.5	40	Endpoint	N/A	192.32	0.027	4.0
Model 6	Geo. Bush	CL2	Backside	20.5	458	Log	0.327	141.903	13.381	4.0
Model 7	Geo. Bush	CL1	Frontside	20.5	40	Endpoint	N/A	213.42	-0.023	4.0
Model 8	Geo. Bush	CL2	Frontside	20.5	40	Endpoint	N/A	165.51	0.064	4.0
					Average Predicted Service Life =					**3.9**
Yellow Thermoplastic - Sealcoat										
Model 1	FM 159	CL	Backside	22.0	220	Log	0.462	141.195	-7.2319	0.8
Model 2	FM 159	CL	Frontside	22.0	220	Log	0.701	184.985	-11.566	4.0
Model 3	FM 974	CL	Backside	21.9	40	Endpoint	N/A	161.45	-0.079	2.1
Model 4	FM 974	CL	Frontside	21.9	360	Linear	0.255	171.469	-0.0794	2.5
Model 5	US 79	CL1	Backside	8.4	100	Endpoint	N/A	130.606	0.012	4.0
Model 6	US 79	CL1	Frontside	8.4	100	Endpoint	N/A	157.02	0.017	4.0
Model 7	US 79	CL2	Backside	8.4	40	Endpoint	N/A	154.91	0.012	4.0
Model 8	US 79	CL2	Frontside	8.4	40	Endpoint	N/A	164.09	0.019	4.0
Model 9	FM 2818	CL	Backside	7.7	40	Linear	0.509	150.607	-0.1868	0.7
Model 10	FM 2818	CL	Frontside	7.7	40	Linear	0.831	193.412	-0.3645	0.7
Model 11	US 79	CL3	Backside	8.4	80	Endpoint	N/A	142.25	0.034	4.0
Model 12	US 79	CL3	Frontside	8.4	160	Linear	0.199	141.082	0.0718	4.0
					Average Predicted Service Life =					**2.9**