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Green Bike Lane Evaluation for Florida Pavements

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16. Abstract

The objectives of this project were to identify the causes of the premature failure of Florida's green-colored pavement markings (GCPMs) and to produce guidelines and improved specifications for the future installation and testing of new GCPM materials. The researchers reviewed relevant literature, interviewed contractors and vendors, visited existing GCPM sites in Florida, and performed laboratory testing on GCPM materials.

In the field, the researchers evaluated four types of GCPM materials across 32 site installations. The materials included preformed thermoplastic, epoxy-modified acrylic, epoxy-resin, methyl methacrylate, and nondurable paint. While many installations were successful, some were severely distressed and failing, as noted by cracking, pavement deterioration, delamination, wear, color degradation, etc. The probable causes range from poor installation methods, moisture movement, shrinkage, thermal incompatibility, susceptibility to UV light, and traffic abrasion.

In the laboratory, the researchers conducted pull-off testing to validate field observations of substrates, evaluated the long-term friction and color performance of GCPM materials, and assessed a thermal incompatibility test for screening GCPM materials. The pull-off test correctly ranked substrate strength. The color of GCPMs did not degrade after 150,000 polisher cycles except for one material, which wore away. Also, GCPMs exhibited a near-constant friction level after 20,000 polisher cycles. GCPMs prone to environmental effects were identified under 250 exposure hours in a weatherometer. Lastly, a modified ASTM C884 test was not an adequate test for measuring the effect of thermal incompatibility between the substrate and GCPM materials.

Finally, the research team revised the Florida Department of Transportation specifications and test methods for GCPM and materials and provided recommendations. In addition, a guidelines document about GCPMs for bicycle facilities was developed for a general audience.

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) is committed to the safety and comfort of bicyclists and pedestrians, who often interact with motor vehicles in a shared roadway environment. In 2012, FDOT began experimenting with green-colored pavement markings (GCPM) to delineate and enhance the visibility of bicycle-vehicular conflict areas. FDOT adopted the design and installation requirements for green-colored pavement for bike lanes, found in the *Manual of Uniform Traffic Control Devices* (MUTCD) (see Interim Approval 14). Aside from color requirements and friction considerations, the MUTCD gives no direction for material properties and best application practices to ensure long-term performance.

The current FDOT developmental specifications for GCPM installation and material properties are Section 714 and Section 976, respectively, and the material test method is FM 5-622. Various materials and vendors have been added to the Approved Product List (APL), but some GCPM installations are prematurely failing (e.g., cracking, pavement deterioration, and delamination). As a result, FDOT contracted the Texas A&M Transportation Institute to identify the causes of the premature failures and to produce guidelines and improved specifications for future installations and material testing. The researchers reviewed relevant literature, interviewed contractors and vendors, visited existing GCPM sites in Florida, and performed laboratory testing on GCPM materials.

Field Evaluation

In the field, the researchers visited 30 GCPM installations representing four material types: 13 preformed thermoplastic installations, 12 epoxy-modified acrylic, one epoxy, one paint, and three methyl methacrylate (MMA). Most GCPMs were installed on dense-graded friction course (DGFC), and a few were installed on open-graded friction course (OGFC) and concrete.

- About 25 percent of the installed thermoplastic failed. These were about three to five years old. The thermoplastic GCPMs performed well, but poor surface preparation and installation methods can result in delamination.
- About 35 percent of the epoxy-modified acrylic installations were severely distressed. These were all between two and three years old. This was likely caused by thermal incompatibility, moisture susceptibility, excessive application thickness, and accelerated drying. Distress was worse for large area markings, in areas closest to gutters and ditches, and on the weaker pavement. The specific material formulation was especially susceptible to shrinkage.
- The one epoxy installation, about four years old, had significant aggregate loss, which can occur if the epoxy layer is too thin. It also had severe UV discoloration.

- The MMA installations, all about four years old, had poor wear resistance and quickly faded as the substrate surface became exposed. The treatment may have required a better wear-resistant aggregate to protect the binder, or the binder itself was not formulated to have adequate strength.
- Poor or unsuitable substrate could have contributed to some of the cracking and delamination failures. The team noted that all GCPM installations performed poorly on OGFC. One site on low-density DGFC (air voids > 10 percent) also had a failure.

Laboratory Evaluation

The laboratory evaluation involved a series of sub-studies, each addressing a different research question. These included evaluation of friction and color performance with polishing, assessment of an accelerated weathering test to qualify GCPM materials, validation of field observations of substrate strength with the pull-off test, and assessment of a thermal compatibility test to prequalify GCPM materials.

- The color of GCPM materials did not degrade with polishing, though the polymer cement sample wore away, exposing the substrate.
- Thermoplastic, epoxy-acrylic, and one MMA, currently approved in Florida, narrowly passed the friction criterion. An MMA from a different vendor failed.
- The friction coefficient before polishing was high and decreased to a relatively constant value after 20,000 cycles.
- An accelerated weathering test, based on ASTM D4956 (ASTM, 2019), distinguished among materials with good and poor colorfastness. Color degradation trends after 250 exposure hours correlated with performance after 1,000 exposure hours.
- The pull-off strength was higher for substrates with lower air voids, which might explain why more substrate failures in the field were noted on less compacted DGFC and OGFC.
- A modified ASTM C884 test did not adequately measure the effect of thermal incompatibility between the substrate and GCPM materials. The test was also demanding in terms of materials and labor.

Recommendations

The research team used the gathered data to develop GCPM guidelines and recommend improvements to the FDOT specifications and test method. Recommendations include:

Dev Section 714 – Green-Colored Pavement Markings

- GCPM applications on OGFC are not recommended and must first be approved by the State Materials Office.
- For preformed thermoplastic, have installers mechanically blast or abrade surfaces, according to the material provider's recommendations, on concrete and aged asphalt.
- To improve bicycle ride quality, allow thinner skip line markings for preformed thermoplastic.
- Divide the "Two Reactive Component Pavement Marking System" material into two material types: "Two Reactive Component System" for epoxy resin and MMA, and "Two Reactive Component Durable Paint System" for epoxy-modified acrylic.
- The durable paint system is limited to lower conflict areas. It must be spray applied, each coat in multi-coat applications must completely dry, and drying cannot be accelerated by applying heat.

Dev Section 976 – Green-Colored Pavement Marking Materials

- Divide the "Two Reactive Component Pavement Marking System" material into two material types: "Two Reactive Component System" and "Two Reactive Component Durable Paint System."
- The two reactive component system must have a high solids content of 80 to 100 percent.
- The durable paint system is a modified waterborne paint that includes two reactive components. The material must pass a curl test to determine shrinkage potential. The test and criterion have not been fully developed.
- Add a color requirement to stay within the color box after 240 exposure hours (10 days) of accelerated weathering.

FM 5-622 – Florida Test Method for Evaluation of Pavement Markings Materials with Friction Requirements

- Add weatherometer exposure testing to qualification (Part A). Provide default exposure settings detailed in the report (Table 4-7) and an exposure time of 240 hours (10 days).
- For field follow-up testing, add cleaning the GCPM surface prior to testing with the colorimeter.

The guidelines, titled *Green-Colored Pavement Markings for Florida Bicycle Facilities*, were written for a broad audience including FDOT designers, engineers, inspectors, private contractors, and academia. The guidelines mirror the proposed specifications and incorporate other best practices. They will be accessible online or by contacting the FDOT State Materials Office.

Further Research

The team recommends further research on the following topics:

- Development of a curl test to measure the shrinkage potential of liquid coatings.
- Evaluate a water absorption test for durable paint materials.
- Comparison of previous generation (System A) and next generation (System B) epoxy-modified acrylic paints.
- Cost-effectiveness of each GCPM material type for different levels of traffic conflict.
- Cost-effectiveness of manually applied GCPM versus automated application systems.
- Colorfastness of different formulations of epoxy systems.
- Wear resistance of other MMA products.

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CHAPTER 1
INTRODUCTION

Problem Statement

The Florida Department of Transportation (FDOT) is committed to the safety and comfort of bicyclists and pedestrians, who often interact with motor vehicles in a shared roadway environment. In 2012, FDOT began experimenting with green-colored pavement markings (GCPMs) to delineate and enhance the visibility of bicycle-vehicular conflict areas. FDOT adopted the design and installation requirements for green colored pavement for bike lanes, found in the *Manual of Uniform Traffic Control Devices* (MUTCD) (see Interim Approval 14). Aside from color requirements and consideration for friction, the MUTCD gives no direction for material properties and best application practices to ensure long-term performance.

The current FDOT developmental specifications for GCPM installation and material properties are Sections 714 and 976, respectively, and the material test method is FM 5-622. A variety of materials and vendors have been added to the approved product list (APL), but some of the GCPM installations are prematurely failing (e.g., cracking, pavement deterioration, and delamination). The long-term performance of the GCPMs could not be ensured by the current practices. Therefore, there was a need to deepen the body of knowledge and improve the state of the practice for GCPMs in Florida.

Goals and Objectives

This research aimed to identify the causes of premature failure of Florida's GCPMs and to produce guidelines and improved specifications for future installations and material testing.

The research objectives were:

1. Review the national experience of GCPMs through a literature search and interview with industry experts. Identify and document best practices.
2. Conduct a comprehensive field evaluation of Florida's GCPM installations and identify causes of premature marking and pavement failures.
3. Identify alternative GCPM materials, test methods, and installation methods that may reduce costs and/or increase the pavement performance while effectively delineating bicycle lanes. Conduct laboratory experiments to evaluate these products and methods.
4. Develop Florida guidelines for GCPMs and update the existing GCPM specifications and test methods.

Outline

The report is divided into the following five chapters based on the tasks performed in this research project. In addition, the products of the project (i.e., Specifications, Best Practice Proposed Test Method, and Guidelines) are attached as parts of the appendices of this report.

1. Introduction.
    - Problem statement.
    - Goals and objectives.
    - Outline.
2. Literature Review and Industry Interviews.
    - GCPM materials.
    - Performance requirements.
    - Installation.
    - Failure and reinstallation.
    - Case studies.
3. Assessment of Florida's GCPM Installations.
    - Installation types and locations.
    - Wear and distress performance.
    - Color performance.
    - Bond strength.
4. Detailed Lab Tests on Florida GCPM Materials.
    - Pull-off test.
    - Polish, friction, and color test.
    - Accelerated weathering.
    - Thermal compatibility.
5. Conclusion.

CHAPTER 2

LITERATURE REVIEW AND INDUSTRY INTERVIEWS

The researchers reviewed the literature and interviewed GCPM industry experts to understand the state of the practice. They focused on the topics of GCPM materials, material and installed performance requirements, installation methods, and national experience in the literature.

The researchers primarily searched for peer-reviewed research studies and publications by state and federal agencies. As it became apparent that the literature on GCPMs was limited, the researchers expanded the review to include some non-technical articles. They also reviewed studies of red-bus lane installations since the same material types can be used for GCPM.

The researchers interviewed suppliers, stakeholders, and a material testing laboratory. The interviews covered a wide range of topics, including current materials in the market, construction procedures, visibility performance, maintenance, distress, and compliance tests (Nyamuhokya and Wilson, 2020). The interview questionnaire is in Appendix C.

GCPM Materials

GCPMs are available in a wide variety of material types. Generally, they consist of pigmented resin and an embedded aggregate. The resin provides high-contrast visibility, bonds to the pavement, and holds the aggregate. The aggregate provides friction and may also be colored. Seven material types are:

- Preformed thermoplastic.
- Epoxy-modified acrylic paint.
- Epoxy.
- Methyl methacrylate (MMA).
- Polymer cement slurry.
- Waterborne paint.
- Colored asphalt.

Commonly embedded aggregates are silica sand, aluminum oxide, bauxite, corundum, crushed green glass, crushed painted glass, and glass beads. Some nondurable paint installations, however, do not contain aggregate. In addition, colored asphalt does not require specialty aggregates but uses typical asphalt mixture aggregates.

The behavior and cost vary across the material types, as shown in Table 2-1. Even within a material type, the performance can still vary depending on the underlying chemistry, formulation (additives, ratios, aggregate type), and installation method (thickness, uniformity).

Table 2-1. GCPM Materials.

Material Type*	Total Binder Thickness (mils) *	Bond Strength	Resistance to…			Material Cost
			UV**	Moisture	Wear	
Preformed thermoplastic	90 to 125 (FDOT requires 125)	High***	High	High	High	High
Epoxy-mod. acrylic	30 to 50 wet 18 to 30 dry (several layers)	Mod	Mod-High	Mod	Mod	Mod
Epoxy	30 to 50 (1 or 2 layers)	High	Low	High	High	High
Methyl methacrylate	30 to 60 (1 or 2 layers)	High	High	High	High	High
Polymer cement	80	Low	Low	Low	Low	Mod
Waterborne paint	15 to 30 wet	High	High	Mod	Low	Low
Colored asphalt	Layer design	NA	Unknown	High	Low	Very High

* *For binder only. Embedded aggregate type can vary and may add thickness.*

** *Color-fastness largely depends on the selected pigment.*

*** *Highly dependent on surface preparation.*

The following is a brief description of each of the GCPM materials.

Preformed Thermoplastic

Thermoplastic is a plastic made from polymer resins that liquefy when heated and harden when cooled. For GCPM installation, the thermoplastic is typically produced in preformed sheets that are configured on the pavement (Figure 2-1). Preformed thermoplastic sheets may be embedded with aggregates such as corundum (aluminum oxide) to improve and maximize friction performance. Thermoplastics adhere well on both asphalt and concrete with proper preparation. Preformed thermoplastic is popular for urban installations because of its fast application time and durable performance. Preformed thermoplastic can serve up to an average of five years or longer, depending on the existing pavement's quality.

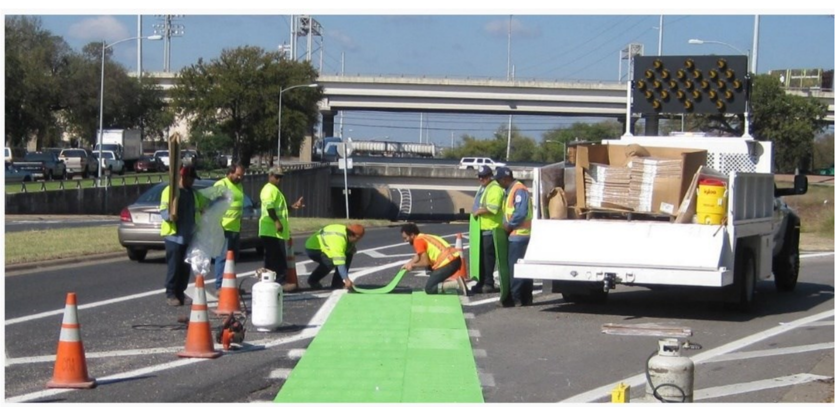


Figure 2-1. Preformed Thermoplastic Installation in Austin, Texas (Brady et al., 2010).

Epoxy-Modified Acrylic

Epoxy-modified acrylics (or epoxy-acrylic) are waterborne acrylic paints that incorporate a two-part epoxy system to improve bond strength and durability (NACTO, 2020). These are applied using commonly available manual and automated paint spray systems (Figure 2-2). They can also be applied with rollers, squeegees, and brooms. Epoxy-modified acrylics adhere well to most surfaces. Sand or aggregates are added when mixing or dropped onto the surface afterward to improve friction. Epoxy-modified acrylics are ideal for corridor treatment (along the length of bike lanes) with low-volume traffic conflicts. However, they can withstand heavy traffic wear if correctly designed with polish-resistant aggregate.

Two epoxy-modified acrylics can have different underlying chemistry that makes notable changes in performance. Paints with the traditional chemistry (System A) are stable for several hours, even days, after mixing. However, they dry slowly when applied and must be built up in multiple layers. They are also more prone to shrinkage. Newer chemistry (System B) reacts and cures much faster, so it can be applied in a single thicker layer. These materials exhibit less shrinkage. They also have a shorter pot-life which must be considered during installation. On average, the lifetime could range from three to five years (NACTO, 2020).

Figure 2-2. New Epoxy Bike Lane Installation, Pennsylvania (NACTO, 2020).

Epoxy

Two-part epoxy, with 100 percent solids, is a thermosetting compound that achieves a very high bond strength and forms a durable coating. This system behaves very differently than epoxy-modified acrylic. The epoxy resin (Part A), usually pigmented, is combined with the hardener (Part B) to start an exothermic chemical reaction. The mixed liquid is spread using squeegees.

Aggregate is dropped onto the spread epoxy before it gels and continues to cure for the next few hours. While epoxy is strong, it can generate pavement issues because it is so stiff and not thermally compatible. Epoxy is less forgiving during application than some other treatments.

Methyl Methacrylate

MMAs are two-part liquids comprised of a resin and an activator. Like epoxies, they are typically applied by hand with a squeegee and a roller (Figure 2-3). The MMA is typically blended with sand or aggregates to achieve desired skid resistance properties (Transpo Industry, 2021). MMA takes a shorter time to cure (less than an hour) than epoxy. In addition, it typically has higher abrasion resistance than other treatments. (NACTO, 2020). Furthermore, MMA products can be reapplied on top of existing layers (NACTO, 2020; Transpo Industry, 2021). The MMA life could range from three to six years (Koetsier et al., 2016). As for most GCPM, inferior substrates and vehicle traffic conflicts affect MMA's longevity.

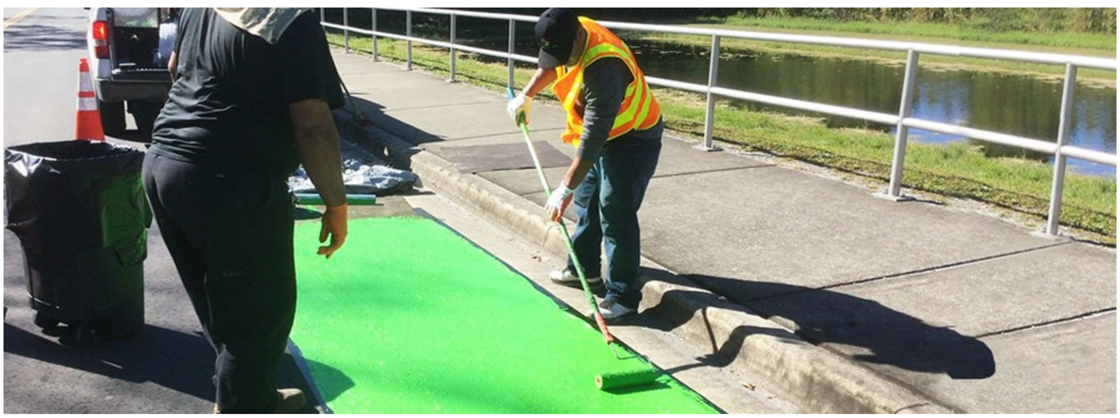


Figure 2-3. Application of MMA Product (NACTO, 2020).

Waterborne Paint (Nondurable)

Paints are commonly used for pavement marking. They are readily available and lower in price compared to other GCPMs. Nonetheless, they are not durable under traffic and are cost-effective only along corridors with little or no vehicle traffic (Figure 2-4). While individual cases may vary, waterborne paints have low durability. Thus, lanes treated with paints may require reapplication within a year (NACTO, 2020). Paints are typically mixed with sand to improve friction. Depending on the traffic and weather (e.g., snowy winters, sunlight, etc.), it can last six months to two years.

Figure 2-4. Paint Treated Bike Lane in Pittsburg, Florida.

Polymer Cement Slurry

This material, also known as “ultra-thin polymer-modified cement slurry, is comprised of fine sand, friction aggregate, polymer, fibers, and admixtures. It has an ultrathin application of 60-75 mil. Ninety percent of polymer cement slurry application is on asphalt pavements (according to the product interviewee). Its installation includes spraying the material over a stencil to create a patterned marking (Figure 2-5). Because it is patterned and not a continuous treatment, shrinkage and thermal cracking are eliminated, with only microcracking around the edges of the pattern (Koetsier et al., 2016). Also, the material is less susceptible to UV exposure than most used green bike lane materials. The material is not affected by salts or oils. The downside of this product is that it could leak out if not finished with a sealer on top. The sealer prevents leaching out and provides a glossy appearance (Koetsier et al., 2016). Depending on traffic volume, the polymer cement slurry can last up to 10 years (according to the product interviewee).

Figure 2-5. Polymer Cement Slurry. (Tensar International, 2021)

Colored Asphalt

The colored asphalt GCPM is the same as standard Asphalt but with added colored pigment (Figure 2-6). The colored asphalt may be installed as a thin layer over conventional asphalt to reduce cost. Asphalt is usually black, but plants can also produce clear asphalt with the refinery. If black asphalt is used, 5 percent of colored pigment is typically used. When clear Asphalt is used, only 1–2 percent is needed (Furth., 2012). The colored asphalt layer is applied as the final surface layer on new pavement, whereas on old pavement, it requires milling of the surface before the installation (NACTO, 2020; Furth, 2012). Colored asphalt lanes offer skid resistance typical of asphalt concrete. Nevertheless, it has poor retroreflective qualities (City of Burlington, 2017). The cost of colored Asphalt is about 30 percent more than black Asphalt, and the longevity of colored asphalt is the same as regular black asphalt.

Figure 2-6. Colored Asphalt Bike Lane: New and Nine Years Old.

Performance Requirements

The researchers found four documents that specify the GCPM material performance. The first is the FHWA-MUTCD 2016 Interim Approval 14 memo, which has requirements for color and consideration for friction. The following two are from FDOT: one for installation (Developmental Section 714, Green-Colored Pavement Markings), and one for materials (Developmental Section 976, Green-Colored Pavement Marking Materials). On the other hand, the American Association of State Highway and Transportation Officials (AASHTO) is drafting a standardized Specification for Durable Green Bike Lane Surface Treatments for Asphalt and Concrete Pavements with Exposure to Vehicular Traffic (AASHTO, 2019).

Furthermore, FDOT has a test method to qualify GCPM materials (FM 5-622). In Florida, a material must first meet laboratory friction and color requirements and then maintain friction, wear, and acceptable pavement condition for three years in a field installation (FDOT, 2014).

The following sections detail the laboratory and field performance requirements of GCPM systems.

Color

All materials installed on state-owned roadways must satisfy the chromaticity (x, y) and luminance (Y) requirements in the FHWA-MUTCD 2016 memo. The most recent target "color box," which is also adopted by FDOT, is shown in Table 2-2 and illustrated in Figure 2-7. A study by the American Traffic Safety Services Association (ATSSA) recommended a tighter color box with less yellow color allowed (also illustrated), but at the time FHWA elected to use the wider box. While not of any practical significance, the right-most point of the current color box was accidently selected outside of the defined chromaticity plot. Some vendors admit to struggling to meet the color box specification, while others stated it is easy to satisfy (Nyamuhokya, 2020).

Table 2-2. Daytime Chromaticity Coordinates

Chromaticity Coordinates	X1	Y1	X2	Y2	X3	Y3	X4	Y4
FHWA, FDOT	0.230	0.754	0.266	0.460	0.367	0.480	0.444	0.583
ATSSA Proposed	0.230	0.714	0.266	0.460	0.367	0.480	0.367	0.583

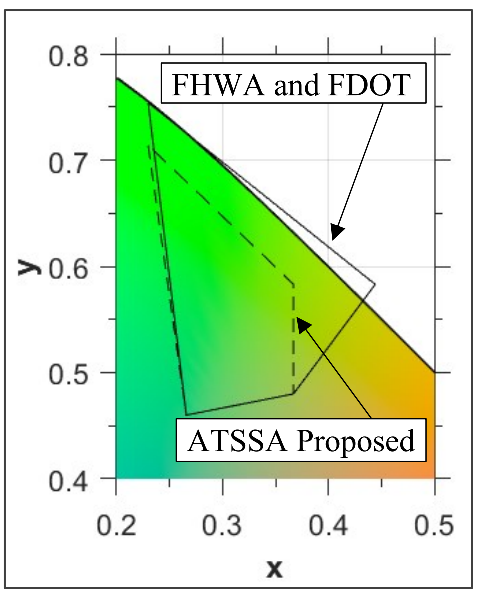


Figure 2-7. Green Color Box (Current Specification and Proposed).

In addition to meeting the color chromaticity, there are luminance (Y) requirements: a minimum of 7 and a maximum of 35. After noting that installed treatments typically darken over time, FDOT adopted a higher minimum luminance (Y) of 15. FDOT does not have a maximum in their specification.

Under weather exposure, there is no requirement to maintain color long-term, even though GCPMs can fade, darken, or change hue after exposure to UV light and other environmental conditions. A colorfastness requirement could be implemented with simulated climate exposure in a Weatherometer machine. However, FDOT has no guidelines for using a Weatherometer to approve pavement markings. While exposure testing could last for over 1,000 hours, the AASHTO guidelines indicate that 144 hours of UV light exposure is enough to identify inferior green bike lane materials. It should be noted that the AASHTO guideline uses ASTM G154 (ASTM, 2016), whereas the research used ASTM D4956 (ASTM, 2019).

Friction

The MUTCD documents state to consider friction needs for bicyclists. FDOT uses the three-wheel polisher and the dynamic friction tester (DFT) to assess the long-term performance of GCPM products (Figure 2-8). GCPM materials must retain a DFT μ (mu) value of 50 after 150,000 cycles. Then in a field trial, they must maintain a μ above 40 after three years. Most suppliers willingly comply with this friction requirement. Other labs use the British Pendulum Tester for friction evaluation (Future Labs, 2014; Nyamuhokya, 2020). Some interviewees suggested that the polisher and DFT, once standardized, could be adopted by manufacturer's labs for long-term approval of the materials.

Figure 2-8. Three-Wheel Polisher and Dynamic Friction Tester.

An opinion from the GCPM vendors was that there should be friction criteria to cater to different applications (higher friction and durability for higher demand). GCPM study by FDOT in 2017 indicated that all the materials tested in the field passed the initial friction test (Offei et.al 2017).

Wear

FDOT requires that the GCPM have no more than 15 percent wear in field installations (i.e., less than 15 percent of the underlying surface is exposed). GCPM wear could happen because of aggregate and binder loss under traffic or from treatment delamination.

The draft AASHTO specification uses an abrasion resistance test of the combined binder-aggregate systems to quantify the GCPM wear. The associated test is ASTM D4060 (Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser) (Figure 2-9). Epoxy and MMA resin systems should lose no more than 85 mg of material after abrasion.

Figure 2-9. Taber Abraser.

Pavement Distress

The Florida specification states that "distress occurring after green-colored pavement marking materials installation may result in removal from the Approved Product Listing (APL). And it is the manufacturer's responsibility to mill, resurface, replace, and install with a product on the APL at no additional cost to the Department" (Dev976GCP). According to the interviewees, epoxy is more likely to cause pavement distresses than thermoplastic and MMA.

Installation

The installation of the GCPM material is typically performed by the contractor and not the material vendor. While GCPMs are relatively novel, the materials themselves are not new to the industry and can be installed by an experienced road marking contractor.

The following factors should be considered before applying GCPM products (contractor interviews; FDOT, 2018; NACTO, 2020).

- The substrate surface must be dry, free of dust and debris, and not oily. Pressure-wash, grind, or shotblast where necessary, depending on the condition of the substrate (NYCDOT, 2012; NACTO, 2020). Thermoplastic is especially benefited by grinding or blasting. Use a primer when advised.

- Make sure a new asphalt surface is well cured. On new asphalt pavement, particularly in high-temperature regions, wait 14 days before applying GCPMs. This ensures that the surface is free from excess surface oils and that the mat has had time to harden by evaporating volatiles and oxidation. New concrete substrates must cure for at least 30 days before installation (NACTO, 2020).
- Except for water-based products, do not install GCPM materials over old marking materials.
- Pay attention to the ambient and surface temperatures. Temperatures between 50°F–100°F work for most materials. The surface temperature for epoxies should be above 60°F. Epoxy curing is much faster when warm. MMA will still cure at temperatures even below freezing.
- Do not apply if rain is expected during application or curing. Water will damage bonding or hinder the complete curing of the materials.
- To improve bonding, use sealers under pre-formed thermoplastic. Spread the sealer evenly to avoid unintended reflection cracking. A sealer is necessary on concrete and old asphalt pavements. The concrete substrate can trap moisture and contaminants (like salt) that may move to the surface and loosen the GCPM and substrate bond. The sealer will prevent moisture from moving into the GCPM (Transline, 2021).
- For preformed thermoplastic, confirm bonding with a chisel test.
- Do not mix products; this could happen when bike symbols are different from the GCPM product.
- Under high traffic conflict, durable GCPM like those with corundum aggregates are preferred. (Corundum aggregates are solid, hard, and have a high resistance to wear.)
- Understand the substrate condition. Some pavement surfaces will have difficulty adhering to some marking materials. For example, a slurry seal does not work well with MMA. The slurry seal does not have enough surface area.

Specific installation techniques for GCPMs vary by product type, as shown in the following sections.

Preformed Thermoplastic

The contractor lays out precut sheets (90–125 mils thick) and then heats them with a propane torch or an infrared radiant heater until melted and fused (Figure 2-10) The operator should monitor the fusion of heat tabs to ensure adequate heating while also avoiding overheating, which will cause discoloration, a rough texture, and material embrittlement.

Figure 2-10. Installation Methods of Preformed Thermoplastic. (NACTO, 2020)

Epoxy-Modified Acrylic

The acrylic/epoxy resin dispersion (Part A) is mixed with the hardener (Part B) and the colorant, according to the manufacturer's instruction. The material is best applied with a spray system to achieve uniform coverage. If the material is made with the older System A polymer chemistry, then it should be applied in multiple layers and allowed to dry between each layer. The total wet film thickness will be between 30 and 50 mils after three to six layers (Eniss-Flint, 2021). Back-rolling or brooming can improve coverage. Primary application with a squeegee or roller, however, is discouraged since it can produce an uneven and overly thick application, which is prone to shrinkage cracking. If using the newer System B chemistry, then apply in a single pass with a sprayer at 30 wet mils (DURATRACK , 2022). In both cases, drop aggregate onto the marking before it cures. A manual spray installation, followed by brooming, is shown in Figure 2-11, and an automated application is in Figure 2-12.

Figure 2-11. Manual Spray and Brush Application of Epoxy-Modified Acrylic.

(Eniss-Flint, 2021)

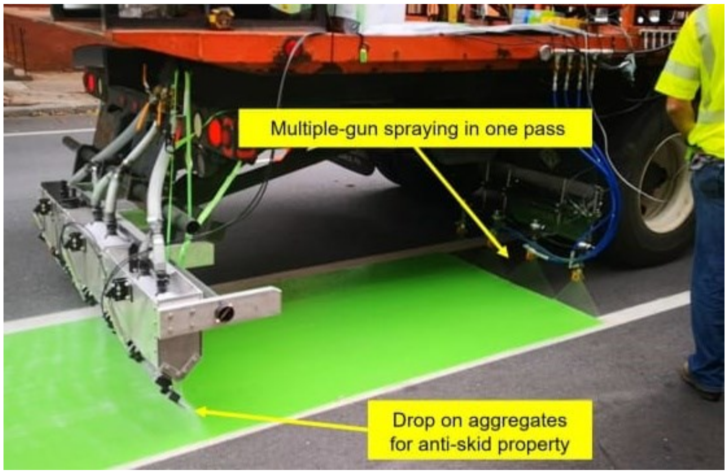


Figure 2-12. Automated Spray Application of Epoxy-Modified Acrylic.

(DURATRACK, 2022)

Epoxy

Prefill any cracks greater than ¼ inch wide with epoxy. Mix Parts A, B, and the colorant according to the instructions. The combined liquid material is then poured onto the pavement and spread using v-notched squeegees. The target thickness is 30 to 50 mils. Observe if any areas require additional epoxy because of uneven surface texture or drain-down. Distribute the specified aggregate onto the spread epoxy until all "wet" spots are covered. If a second layer is required, be lighter on the first aggregate application and apply the layer after the initial set. Once cured, sweep away loose aggregate. The project might need another sweeping after a week or two.

Methyl Methacrylate

Mix the resin and hardener parts, color, and aggregate. Pour the MMA on the pavement surface and spread to 30–50 mils thick with a v-notched squeegee. It can also be sprayed using the correct equipment (Figure 2-13). A coarse paint roller may be used to add texture to the surface. After that, the MMA-treated surface is left to cure for about 20 to 60 minutes, depending on the prevailing weather (Anderson et al., 2018; Transpo Industry).

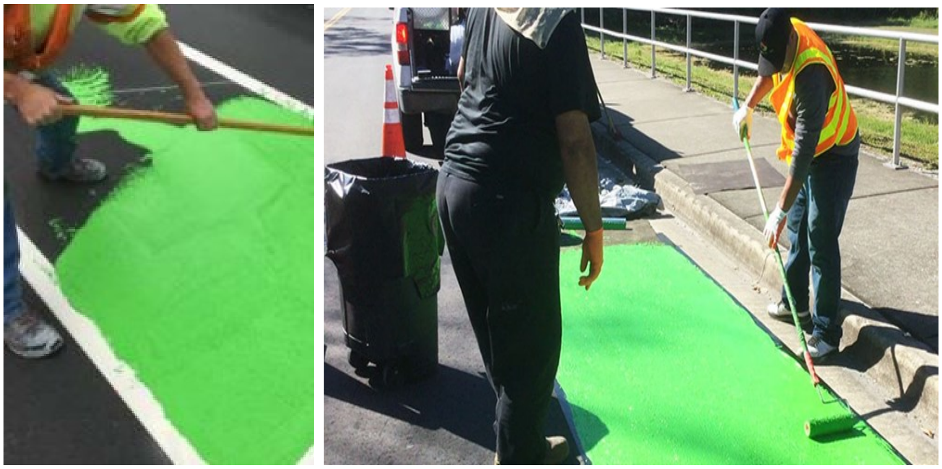


Figure 2-13. Installation of MMA. (Anderson et al., 2018; Transpo Industry)

Colored Asphalt Treatment

Colored asphalt is laid as the top wearing surface. The design, batching, mixing, laydown, and compaction of colored asphalt is the same as typical asphalt concrete. Equipment previously used for normal construction must be cleaned prior to use (Peter Furth, 2012; NACTO, 2020). Figure 2-14 shows the construction of colored asphalt bike lanes (Bicycle Dutch, 2020).

Figure 2-14. Construction of Colored Bike Lane in the Netherlands. (Bicycle Dutch, 2020)

Polymer Cement Slurry

For the polymer cement slurry, the surface is first cleaned, then the bike lane's boundaries to be treated are masked. A stencil is then placed to create patterns. After that, the treatment is sprayed (60–75mils thick) using specialized equipment, followed by removing the stencil before hardening the cement slurry (Figure 2-15). Lastly, the surface is finished with a sealer to protect it from leaching and provide a glossy surface (Koetsier et al., 2016; Tensar International, 2021).

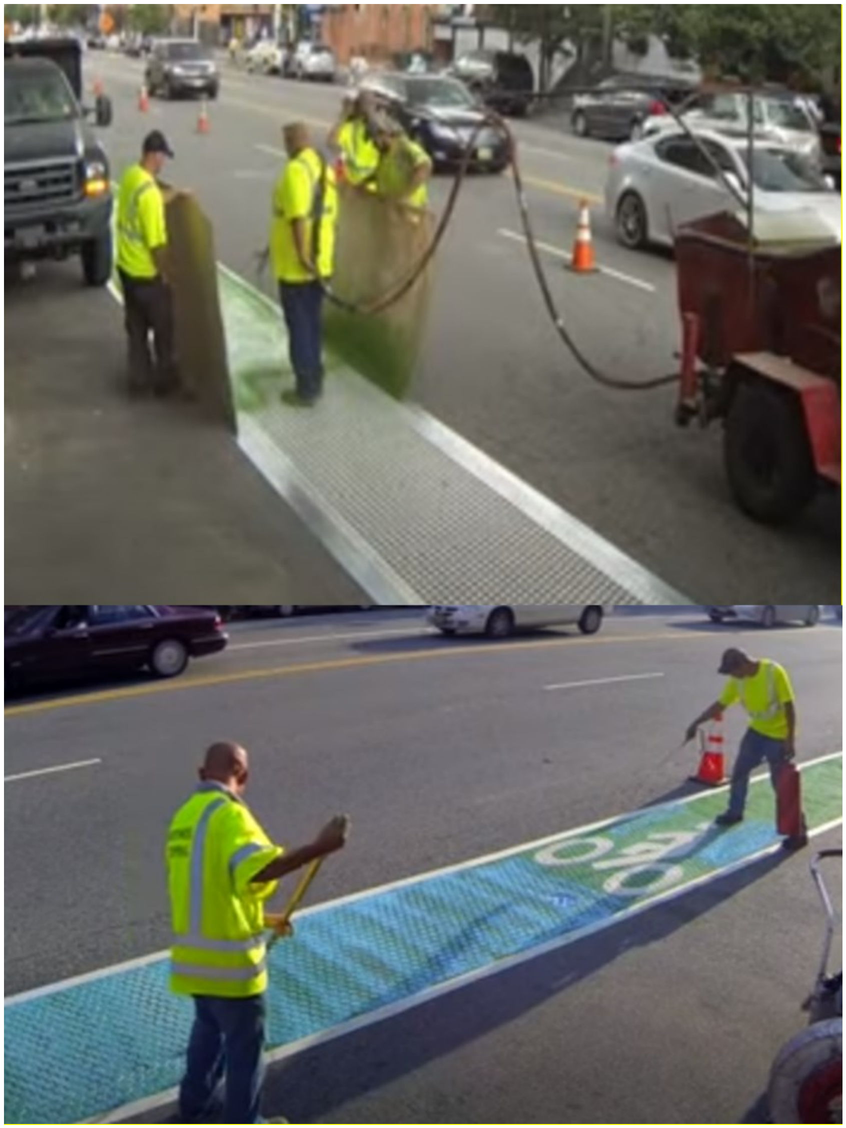


Figure 2-15. Installation of Polymer Cement Slurry. (Tensar International, 2021)

National Experience in the Literature

Despite limited research-focused performance studies on GCPM, as shown through literature searches and interviews, many states and cities are adopting green bike lanes. The following are examples of cities that use green bike lanes. Because of the limited literature, the research team expanded the review to include some nontechnical articles. In addition, the research team reviewed studies about red-bus lane installations since these materials and functionality are very similar to GCPM.

Vermont

In 2018, Anderson et al. reported the performance of three GCPM products installed in Vermont for two years (2018). The products were a preformed thermoplastic and two MMAs. The installation of these products followed the manufacturer's instructions, and the manufacturer had their representative on site. Anderson et al. reported that the thermoplastic product wore out due to turning traffic (2018). Also, the thermoplastic was delaminated and cracked, likely due to moisture and differential expansion with the pavement. The MMA products only wore out due to traffic and showed no chipping, delamination, or cracking.

Austin, Texas

Austin was an early adopter of green bike lanes, especially the thermoplastic treatment. City officials reported that an oil-based coating ("sealer") must be applied on the asphalt surface before installing thermoplastic. Their experience indicated that if the sealer is not well-dried, it burns through the marking. The city officials also reported that poor installation near the I-35 exit led to the quick deterioration of thermoplastic green bike lanes. Water spilled on the surface before the sealer dried off and caused poor bonding and early delamination.

Furthermore, the poor quality of substrates contributed to the quick deterioration of the GCPMs. It was very difficult to uniformly spread the sealer on the deep cracks of the old pavement (Brady et al., 2010). In addition, the city officials recommended applying thermoplastic on fresh asphalt (overlay, etc.) because of the difficulties of working with old pavements.

New York City, New York

In 2005, New York City participated in the early FWHA experimental project Evaluation of Solid Green Bicycle Lanes to Increase Compliance and Bicycle Safety. As a result, they treated most of their bike lanes with epoxy GCPM. In 2011, the city officials reported their experiences and findings to FWHA. They noted the following regarding the epoxy GCPM performance (NYCDOT, 2011):

- It has good skid resistance (not slippery when wet).
- Over time, the substrates' defects reappear on the surface as the lane becomes dirty.
- The shade shows up well at night under the street light illumination of the city's high-pressure sodium lamps.
- Maintenance was required every three to five years.

Milwaukee, Wisconsin

The city of Milwaukee uses preformed thermoplastic green for green bike lanes more than other available green markings like epoxy and paints. The city engineers prefer preformed thermoplastic over epoxy and paints because of better durability and skid resistance (City of Milwaukee).

Los Angeles, California

Green-colored bike lanes in Los Angeles comply with FHWA guidelines (IA-14) (Lindley et al., 2011). Also, in Los Angeles, they consider the impact of film shooting in some locations or lanes shared by bikers. LADOT approved a cementitious-based, green-colored material to accommodate all situations.

Red Bus Lanes

Carry et al. (2012) evaluated three colored marking products applied on a New York bus lane. They studied Portland cement, epoxy, and red-colored asphalt-based products. The study concluded that:

- Cement-based products were not an effective red-lane treatment on either asphalt concrete or Portland cement surfaces.
- Epoxy products performed relatively well on new asphalt concrete surfaces. The product performed poorly on fair- to poor-condition pavements.
- Asphalt-based micro-surfacing performed well on both new and existing asphalt concrete surfaces.
- Aggressive pre-treatment, including shot blasting and power washing, improves epoxy street paints on existing asphalt pavements.

Furthermore, Varamini et al. (2016) and Liu et al. (2017) investigated the field's long-term performance of plant-produced red asphalt used for bus lanes in the city of York in Canada. The product consisted of a red aggregate blend, proprietary red pigment, and polymer-modified asphalt binder. The colored surface treatments were tested for surface texture, friction, and visual distress in the field. The investigation indicated that the red-pigmented asphalt has better surface friction properties than epoxy and offers almost the same friction properties as the conventional asphalt mixture without the red pigment. In addition, the researchers reported that the red asphalt mixture lost color faster than epoxy. It was also noted that wearing due to traffic and UV light had more effect on the colored asphalt than on the epoxy. Furthermore, within one year, the red asphalt mixture developed premature thermal and fatigue cracking. The added pigment may have reduced the fatigue life of the asphalt mixture.

CHAPTER 3

ASSESMENT OF FLORIDA'S GCPM INSTALLATIONS

The research team assessed GCPM installations in Florida. The assessment involved visual distress surveys, a color measurement, and coring for subsequent laboratory testing. This chapter presents the site locations, a summary of the observed distresses, color measurements, and core evaluation results.

Installation and Location Overview

The researchers evaluated five types of GCPM materials across 30 installations. The materials included preformed thermoplastic (12 sites), epoxy-modified acrylic (13 sites), epoxy (1 site), MMA (3 sites), and waterborne paint (1 site). The last material, however, is not considered a GCPM material by FDOT specifications. The installations were both on-system (state-owned) and off-system and represented a wide range of traffic exposure severity. Most installations were done on DGFC, and few were installed on OGFC and on concrete. Figure 3-1 is a map of the installation locations. The site details, including location, material type, construction date, substrate type, and substrate age, are presented in Table 3-1. For reference, the Site ID used in this report is the same used in the GCPM installation database maintained by the FDOT State Materials Office.

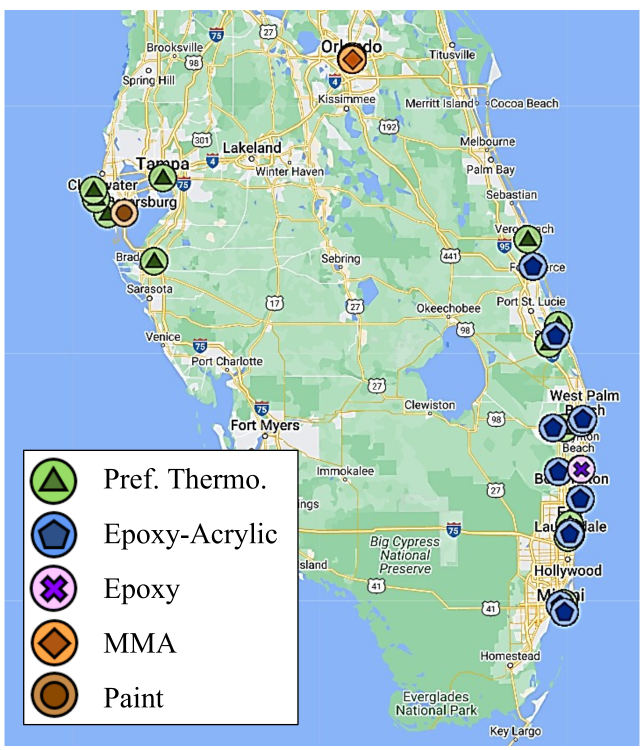


Figure 3-1. Location of Green-Colored Pavement Marking Installations.

Table 3-1. GCPM Installation Details.

Site ID	Location				Green-Colored Pave. Marking		Pavement	
	District	County	System	Description	Material Type	Est. Age at Survey, yr	Type	Est. Age at Install, yr
1	1	Manatee	On	SR43/US301	Pref. Thermo.	3.3	OGFC	0
2	7	Hillsborough	On	SR60	Pref. Thermo.	2.0	DGFC	0
3	7	Pinellas	On	SR699 (Gulf Blvd/106th Ave)	Pref. Thermo.	3.0	DGFC	0
4	7	Pinellas	On	SR699 (Gulf Blvd/CR694)	Pref. Thermo.	3.0	DGFC	0
5	7	Pinellas	On	SR699 (Walsingham Rd/Gulf Blvd)	Pref. Thermo.	3.0	DGFC	0
6	7	Pinellas	Off	1st Ave N. (county project)	Paint	13	DGFC	4
7	4	St. Lucie	On	SR 615 from St. Lucie Blvd to SR-5	Epoxy-Acrylic	2.9	DGFC	0
8	4	Martin	On	EB A1A/SE Ocean Blvd at South River Rd	Pref. Thermo.	2.0	DGFC,Conc	5
10–13	4	Martin	On	Kanner Hwy and I-95 (multiple)	Pref. Thermo.	2.0	DGFC	5
15	4	Indian River	On	SR 656 at Indian River Blvd	Pref. Thermo.	2.0	DGFC	0
16	4	Martin	On	US1 and SE Gran Park Way	Epoxy-Acrylic	1.4	DGFC	0
17	4	Palm Beach	Off	15th St from Australian Ave to Dixie Hwy	Epoxy-Acrylic	1.9	DGFC	Unknown
18	4	Palm Beach	On	EB Okeechobee Blvd at I-95	Epoxy-Acrylic	2.1	DG,OG,Conc	1
19	4	Palm Beach	Off	NE 2nd Ave from George Bush Blvd to 13th street	Epoxy-Acrylic	2.9	DGFC	0
20	4	Palm Beach	On	SR 7 from Clint Moore Rd to Atlantic Ave	Epoxy-Acrylic	2.6	OGFC	0
21	4	Broward	On	N. Ocean Dr. from NE 2nd St to Ne 2nd St. (Road Bends)	Epoxy-Acrylic	3.9	DGFC	0
22	4	Broward	Off	NE 6th Ave from Oakland Park Blvd to Commercial Blvd	Pref. Thermo.	2.8	DGFC	Unknown
23	4	Broward	Off	NE 7th Ave/N Dixie Hwy from NE 13th St. to NE 17th Ct	Epoxy-Acrylic	2.4	DGFC	Unknown
24	4	Broward	Off	NW 9th Ave from Broward Blvd to Sistrunk Blvd	Pref. Thermo.	3.2	DGFC	0
26	4	Palm Beach	On	SR80 Southern Blvd at the Turnpike	Pref. Thermo.	1.5	DGFC	0
27	5	Orange	Off	N. Magnolia Ave from E. Livingston St to E. Colonial Dr.	MMA	3.6	DGFC	Unknown
28, 29	6	Dade	On	MacArthur Cswy	Pref. Thermo.	5	DGFC	0
30	6	Dade	Off	Rickenbacker Cswy	Epoxy-Acrylic	5	OGFC	0
34	4	Palm Beach	On	SR80 at Royal Palm Beach Blvd	Epoxy-Acrylic	1.7	DGFC	2
35	4	Palm Beach	Off	NE 2nd Ave from NE 4th St to George Bush Blvd	Epoxy	3.7	DGFC	0
55	4	Broward	Off	Dixie Hwy from NE 17th CT to Middle River Bridge	Epoxy-Acrylic	2.4	DGFC	Unknown
56	4	Broward	Off	NE 13th Street from NE 4th Ave to NE 9th Ave	Epoxy-Acrylic	3	DGFC	Unknown
57	5	Orange	Off	E Livingston Street from I-4 to Magnolia Ave	MMA	4	DGFC	Unknown
58	5	Orange	Off	Rosalind Ave from Anderson St to Livingston St	MMA	4	DGFC	Unknown
59	6	Dade	Off	SR 968 from SW 2nd Ave. to US-1	Epoxy-Acrylic	3	DGFC	Unknown

GCPM and Pavement Distress Performance

A summary of distresses observed for each site is shown in Table 3-2. Severity is marked as low (L), moderate (M), or high (H). An overall qualitative rating of ‘good,’ ‘fair,’ or ‘poor’ was also made. In general, the researchers found that thermal cracking, delamination, and wear were the three most common distresses in Florida’s bike lanes (Figure 3-2).

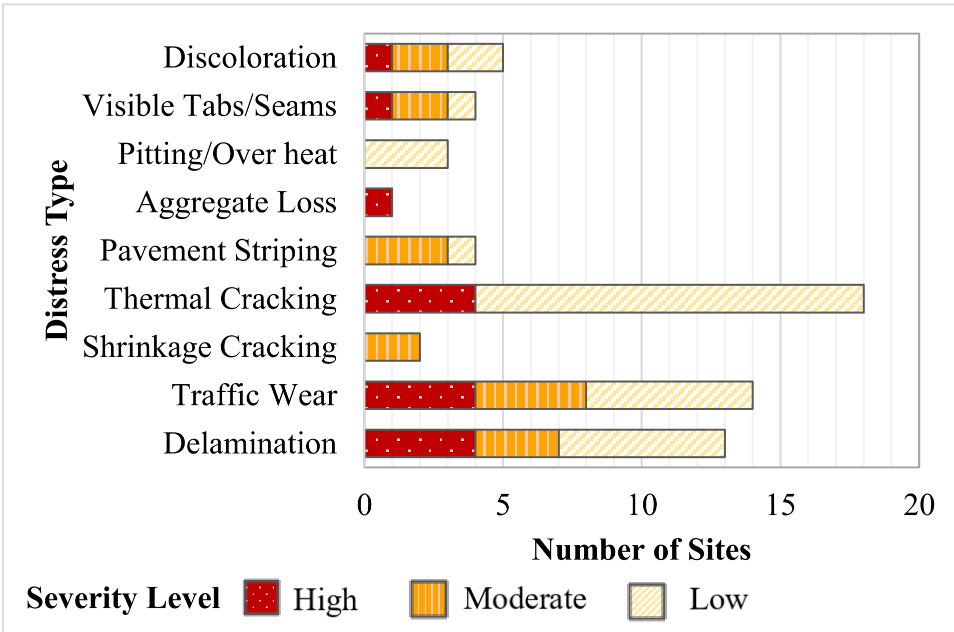


Figure 3-2. Number of GCPM Installations versus Distress Type.

The research team documented the distresses by material type, as shown in the following sections. In addition, the details of the GCPM and pavement distress evaluations site by site are presented in Appendix A.

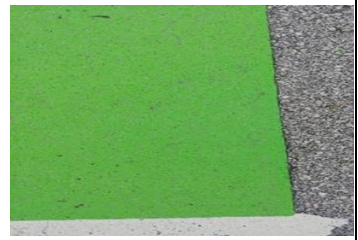
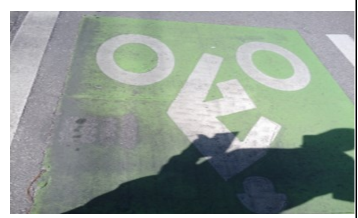
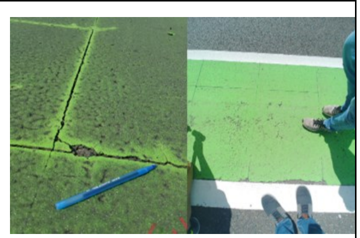
Table 3-2. Observed Distresses on Florida Green Bike Lane Sites.

Site ID	GCPM Material	Substrate	Age (yr)	Distress									Overall Condition
				Delamination	Traffic Wear	Shrinkage Crack	Thermal Crack	Pvmnt. Striping	Aggregate Loss	Pitting/Overheat	Vis. Tabs/Seams	Discoloration	
1	Pref. Thermo.	OGFC	3.3	L			L				H	M	Fair
2	Pref. Thermo.	DGFC	2.0										Good
3	Pref. Thermo.	DGFC	3.0				L						Good
4	Pref. Thermo.	DGFC	3.0				L						Good
5	Pref. Thermo.	DGFC	3.0		L		L						Good
8	Pref. Thermo.	DGFC, Conc.	2.0							L			Good
10 to 13	Pref. Thermo.	DGFC	2.0							L			Good
15	Pref. Thermo.	DGFC	2.0	L			L			L	L		Good
22	Pref. Thermo.	DGFC	2.8	H									Poor
24	Pref. Thermo.	DGFC	3.2	H			L				M		Poor
26	Pref. Thermo.	DGFC	1.5										Good
28, 29	Pref. Thermo.	DGFC	5	H							M		Poor
7NB	Epoxy-Acrylic	DGFC	2.9	H			H	M					Poor
7SB	Epoxy-Acrylic	DGFC	2.9				L						Good
16	Epoxy-Acrylic	DGFC	1.4				L						Good
17	Epoxy-Acrylic	DGFC	1.9	M	M		H	L				M	Poor
18 C	Epoxy-Acrylic	Conc.	2.1										Good
18 O	Epoxy-Acrylic	OGFC	2.1	L	H								Poor
18 D	Epoxy-Acrylic	DGFC	2.1		M								Fair
19	Epoxy-Acrylic	DGFC	2.9	L			L					L	Good
20SB	Epoxy-Acrylic	OGFC	2.6		M								Fair
20NB	Epoxy-Acrylic	OGFC	2.6			M	L						Fair
21	Epoxy-Acrylic	DGFC	3.9	L	L								Good
23	Epoxy-Acrylic	DGFC	2.4	M	L	M	H	M					Poor
30	Epoxy-Acrylic	OGFC	5				L					L	Good
34	Epoxy-Acrylic	DGFC	1.7				L						Good
55	Epoxy-Acrylic	DGFC	2.4	M	L		H	M					Poor
56	Epoxy-Acrylic	DGFC	3		L		L						Good
59	Epoxy-Acrylic	DGFC	3	L	L		L						Good
35	Epoxy	DGFC	3.7						H			H	Poor
27	MMA	DGFC	3.6		H								Poor
57	MMA	DGFC	4		M								Poor
58	MMA	DGFC	4		H								Poor
6	Paint	DGFC	13		H								Poor

Thermoplastic Distress

The research team observed about 12 thermoplastic bike lanes (see Appendix A) and found excessive delamination on sites 22, 24, and 28 (Figures A-5, A-6, and A-7). All these bike facilities were on DGFC substrate. Furthermore, the researchers observed excessive split seams on site 1. The site 1 substrate was OGFC (Figure A-8). Hair cracks and edge cracks were also observed in the majority of the thermoplastic bike lanes; however, the cracks do not pose any aesthetic or structural performance issues. All observed distress on the thermoplastic lanes are summarized in Table 3-3.

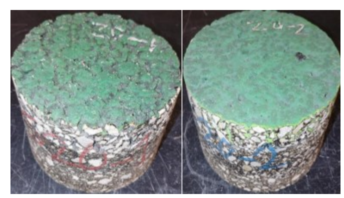
Table 3-3. Thermoplastic Distresses.

Pitting and Overheating Manifests itself as discoloration marks, roughened or pitted texture, or bubbling caused by overheating during installation. Contractor experience and equipment could reduce the problems.	
Edge cracks These are cracks around keyholes and the long stripe lanes and boxes. Mostly these were hairline cracks and not performance issues. These were caused by differential thermal movements of the materials and substrates.	
Delamination In this case, the thermoplastic easily peels off from the surface. The problem could arise from poor preparation during construction (e.g., inadequate heating, dirty, wet surface, rain a few hours after construction, etc.). After construction, sources likely will include trapped moisture, which gradually causes the material to debond.	
Wear Wearing and skid marks were observed in areas exposed to traffic. This problem could be seen on GCPMs next to parallel parking and on turns.	
Splitting seams In this distress, the preformed thermoplastic panels separated along the seams. The problem could be seen in both trafficked and non-trafficked areas.	

Epoxy-Modified Acrylic Distress

The research team surveyed 13 epoxy-modified acrylic sites (see Appendix A). A summary of the observed distresses is shown in Table 3-4. The team observed excessive cracking and delamination on sites 7 northbound (Figure A-13), 17 (Figure A-15), and 55 (Figure A-21). The source of the problem could be compatibility between GCPM and substrate, thick applications, poor construction techniques, or moisture movement. Furthermore, the researchers observed excessive wearing on site 18 (Figure A-16). Similarly, on site 55, the team observed that a pedestrian crossing treated with patterned epoxy had not cracked or delaminated.

Table 3-4. Epoxy-Modified Acrylic Distresses.

Shrinkage cracking A random network of cracks formed throughout the treatment, especially in locations that were applied too thick or using accelerated curing. Most prominent in wide application areas, and less within short key-hole skips.	
Thermal and moisture induced cracking and deterioration Cracking pattern both parallel and perpendicular to the direction of installation. Deterioration immediately around the cracks accelerates, as noted by debonding, delamination, a tight network of cracks, and/or damaged pavement. Larger areas and locations closer to moisture sources more prone to this damage.	
Varying texture In some sites, the epoxy-acrylic treatment was not applied uniformly or with two different techniques (i.e., site 20)—the more pronounced on OGFC substrate. The surface was thick on spots where a squeegee technique was used, and materials penetrated open pores (observed in the lab).	
Wear The wearing was observed in areas of conflict with traffic (i.e., at the entry of properties, next to parallel parking, turns, and exits to highways). The problem was more profound on the OGFC substrate sprayed with epoxy paint.	
Discoloration The typical color of a new green-colored bike lane is lime green; however, the color was dull in some of the epoxy-treated sites, including those under trees (dirty) and in areas of high traffic conflict.	

Epoxy

The team visited only one epoxy-treated site (see Appendix A). The site had aggregate loss (shedding) and discoloration, as shown and discussed in Table 3-5.

Table 3-5. Epoxy Distresses.

Aggregate loss (shedding) This was a pure epoxy resin. Aggregate loss was observed in areas where epoxy mixed with glass was used. The glass, added to provide friction, had popped out of the epoxy.	
Discoloration The typical color of a new green-colored bike lane is lime green; however, the color was dull and almost black on the epoxy site. Epoxy has poor UV resistance and may contribute to the discoloration.	

MMA Distress

The research observed three MMA sections in Orange County (i.e., sites 27, 57, and 58). The sections were about four years old. However, the sections are worn out and need immediate maintenance (Figure 3-3). This particular MMA product seems to have insufficient durability and wears away under traffic too soon, even though other MMA markings tend to be strong and durable.

Figure 3-3. Worn-Out MMA.

Color Performance

The GCPM color performance for the surveyed bike lanes was quantified using a spectrophotometer. The calorimeter determines the daytime chromaticity (x, y) and luminance (Y) of GCPMs (Figure 3-4). Twenty-seven sites were measured for daytime color in the field, and the results were evaluated against the FDOT and FHWA color box. The research team plotted all data points recorded from each site. The measurements were randomly (unbiased) collected to represent different locations on each site. Figure 3-5 shows color readings from five thermoplastic sites that barely fell inside the color box. On the other hand, no epoxy-acrylic or epoxy site passed the chromaticity test. In service, the presence of dirt and debris can affect the color and is not an indication of poor material performance.

Figure 3-4. Green Color Recording Using Spectrophotometer.

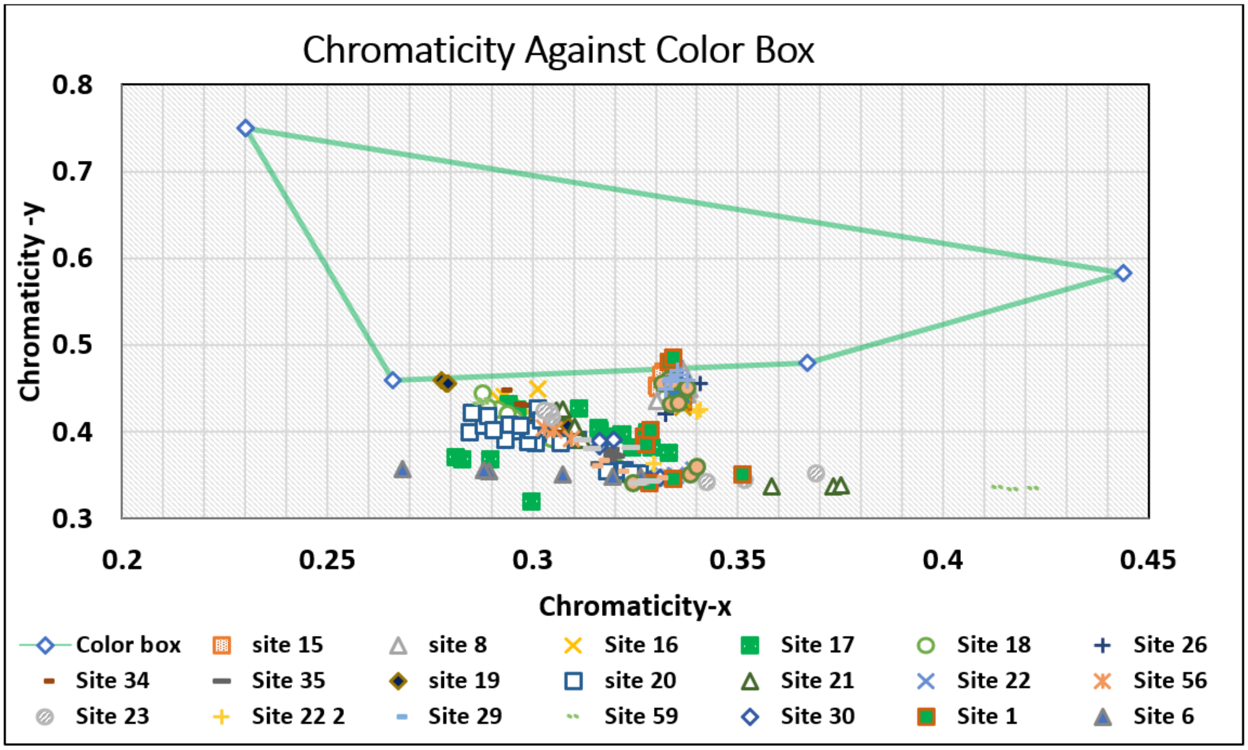


Figure 3-5. Daytime Color for Field-Installed GCPMs.

Furthermore, the research team measured the luminance (Y) of the GCPMs. The average luminance of different sites is shown in Figure 3-6. All areas passed the Y criterion (between 7 and 35). To be precise, all sites 'Y' lies between 7 and 25, and over 50 percent of the site's Y values are above 15.

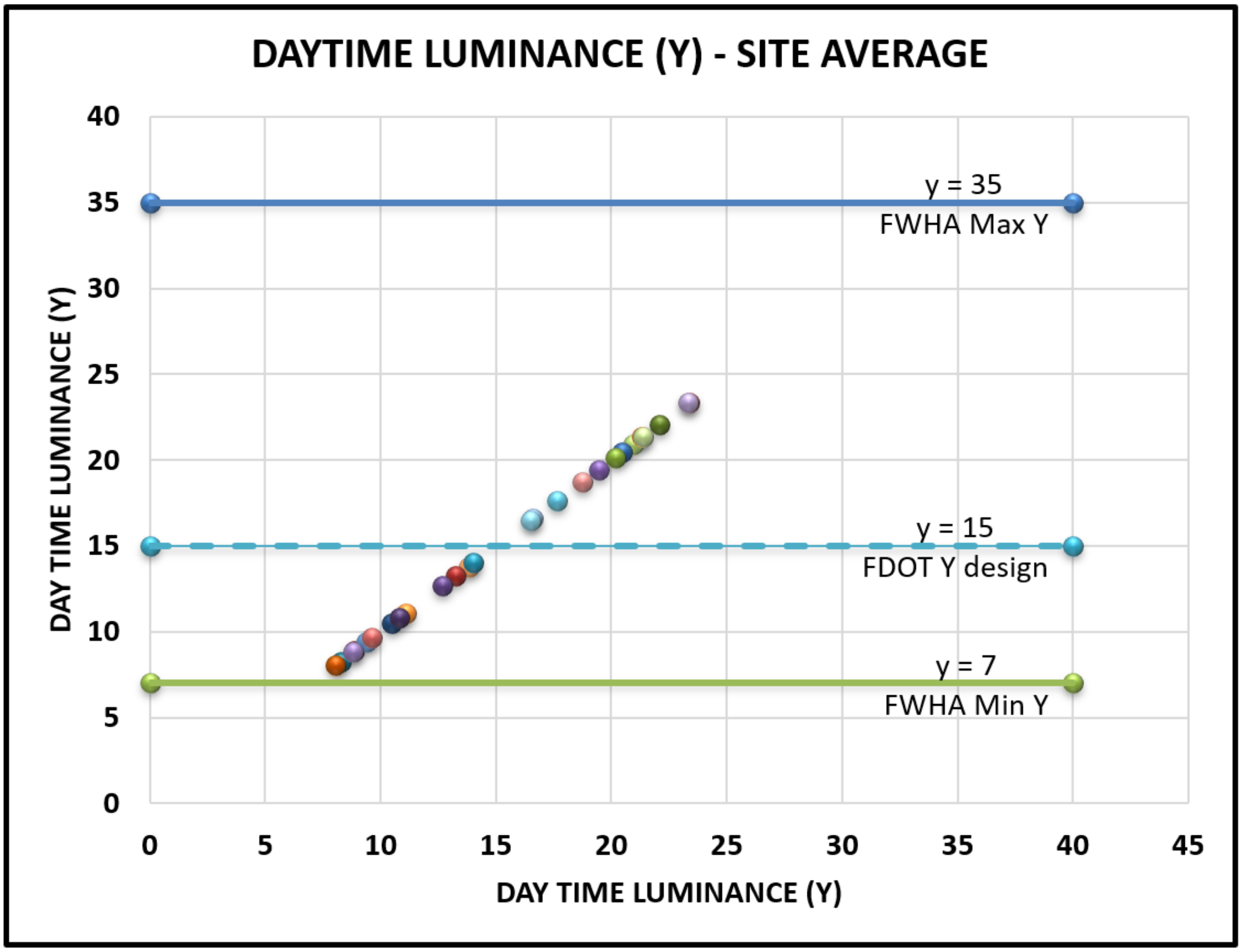


Figure 3-6. Daytime Luminance (Y) Field Test Results.

Core Inspection and Pull-Off Testing

Core Inspection

The research team collected cores from the different GCPM installations in Florida and performed a lab investigation at the Texas A&M Transportation Institute headquarters. The purpose was to investigate the extent and possible cause of distress in the pavements. Distresses limited to the surface could be indicative of the problems related to the GCPMs. For example, on site 8, the researchers observed a crack in the field but could not determine its extent until after lab investigation (Figure 3-7). The results of the core investigation were used to supplement the results of the field survey. Furthermore, the research team conducted pull-off testing on the field-collected cores.

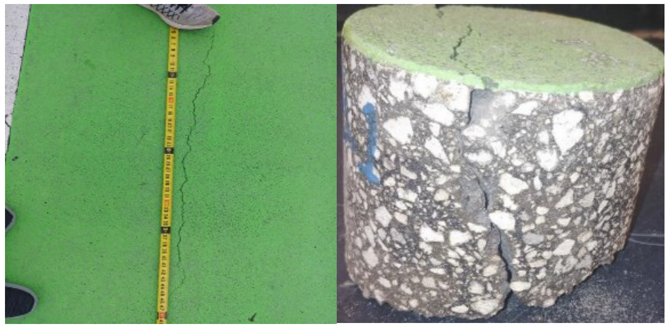


Figure 3-7. Core Showing Extent of a Crack Observed in the Field.

Pull-Off Test

The pull-off test was conducted using the Proceq DY-2 family of automated pull-off testers to determine the bonding strength of the GCPM materials on the Hot Mix Asphalt (HMA) substrate. The testing procedure involves the following steps.

1. Cut a circular groove on the surface and penetrate part-way through the core sample. The specimens were cored 2 inches deep on three locations on the surface to form independent areas for the pull-off test (Figure 3-8).

Figure 3-8. Gluing the Pull-Off Test Loading Discs.

2. Adhere the test disk to the surface using epoxy.
3. Connect the pull-off apparatus to the test disk.
4. Ensure perpendicularity and apply a direct-tension force until the test disc is pulled off. Loading was done at 5 psi per second (Figure 3-9).

Figure 3-9. Pull-Off Test in Progress.

5. Record the failure location and the maximum strength.

Pull-Off Test Failure Mechanism

The researchers clustered all the failure mechanisms into three major groups. Furthermore, the researchers tentatively used 150 psi as a minimum cut-off criterion on an excellent GCPM bond. The criterion was proposed for concrete substrates by AASHTO's draft green bike lanes test guidelines (AASHTO, 2019). The test indicated the following failure mechanisms.

a) **Clean Delamination**: The specimen fails at the GCPM/substrate interface (Figure 3-10). The substrate and treatment are stronger than the bond.

Figure 3-10. Clean Delamination under Pull-Off Test.

b) **Substrate Failure**: Figure 3-11 shows the substrate failing near the bond interface. Possibly due to an inadequate substrate (i.e., low-density substrate), the GCPM surface peeled off with aggregates attached underneath.

Figure 3-11. Substrate Failure near the Interface under Pull-Off Test.

c) Figure 3-12 also shows substrate failure, but this time the breakage occurred deep into the asphalt mixture. The GCPM to substrate bond is stronger than the mixture.

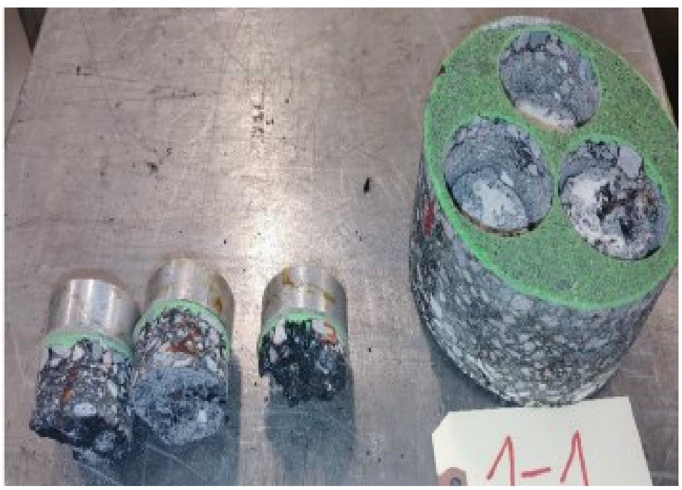


Figure 3-12. Substrate/HMA Failure under Pull-Off Test.

d) **Forced Surface Debond**: Cutting the GCPM surface just enough to expose the substrate (about ⅛ inches) can encourage failure at the interface. As Figure 3-13 shows, the shallow cut still does not guarantee bond failure, since the substrate near the test could still be weaker than the bond. The team demonstrated the forced debond on two epoxy-treated cores (sites 7 and 17) (Figure B-18 and Figure **B-19**), and both produced a bond strength above 150psi. Similar results were observed for the other two specimens that broke at surface level (Appendix B).

Figure 3-13. Forced Surface Debond.

Pull-Off Test Results

Figure 3-14 shows the pull-off test results for 19 specimens (7 thermoplastic and 12 epoxy-modified acrylic). The results indicate that a little more than 50 percent of thermoplastic specimens failed or needed more testing to determine GCPM to HMA bonding strength. Likewise, over 60 percent of the epoxy-modified acrylic specimens fall in the same category. The research team assessed the relationship between age and the GCPMs' performance. Almost all GCPMs were equal to or less than three years and could not show a correlation between age and performance. The extended results of the pull-off tests are shown in Appendix B.

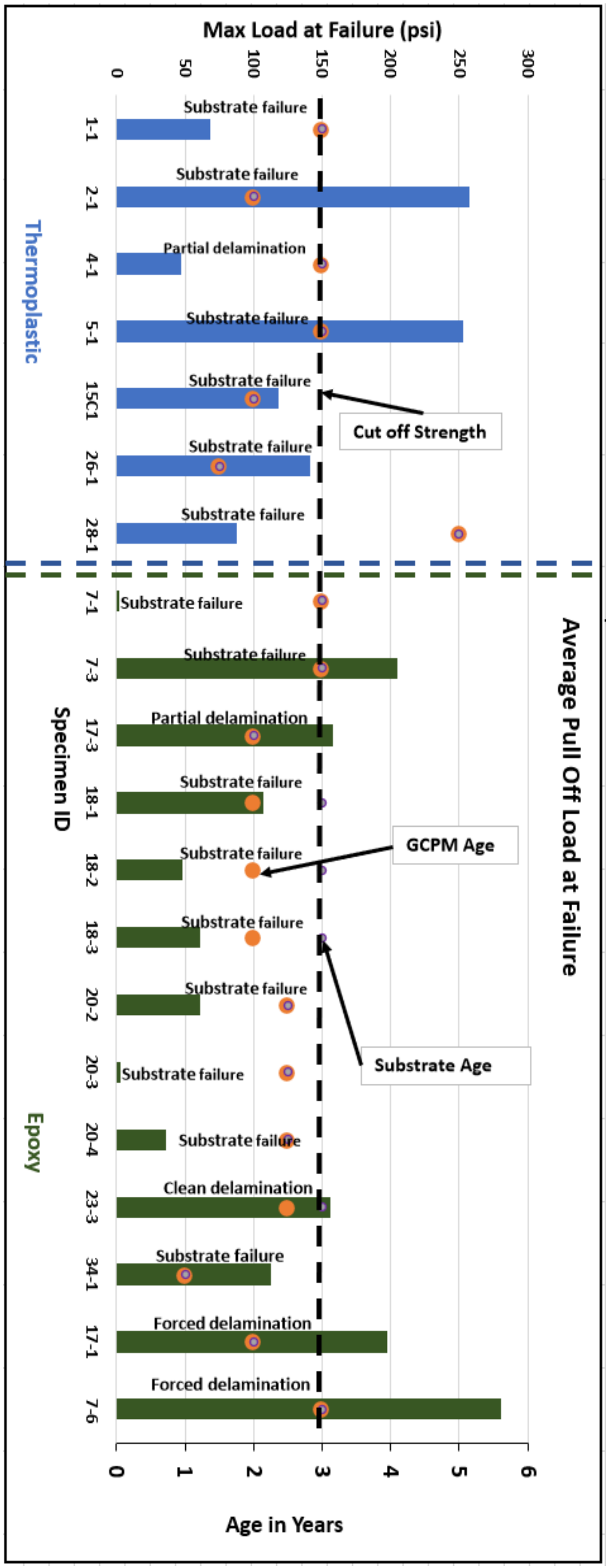


Figure 3-14. Pull-Off Test Results.

CHAPTER 4

LABORATORY EXPERIMENTATION

Based on the literature review, interviews, and field survey, the research team noted four research needs that, if addressed, could improve the state of the practice of GCPMs in Florida. A series of experiments were developed to address each need, as summarized in Table 4-1.

Table 4-1. Laboratory Experiments versus Simulated Distresses.

Research Need	Test Methods	Distress Type
1. Evaluate the friction and color performance of existing and new GCPM materials with polishing.	FM 5-622 Friction measurement with dynamic friction tester. Chromaticity and luminance with a spectrophotometer. Three-wheel polisher.	Friction loss, discoloration, and wear with traffic exposure.
2. Assess an accelerated weathering test to prequalify GCPM materials.	ASTM D4956 Xenon arc and water exposure.	Discoloration with climate exposure.
3. Validate field observations of debonding and substrate failure.	ASTM C 1583 Direct-tension pull-off test.	Delamination with and without substrate failure.
4. Assess a thermal compatibility test to prequalify GCPM materials.	Modified ASTM C884 Modified thermal compatibility test (ASTM between coating and substrate).	Thermal-induced cracking and delamination.

This chapter describes the materials used for laboratory testing then presents the methodology and results of each experiment.

Materials

Several GCPM materials and substrate types were evaluated throughout the experiment. The GCPM materials are detailed in Table 4-2.

Table 4-2. GCPM Materials.

GCPM Material	Aggregate	Application
Preformed Thermoplastic-A (Vendor A)	Embedded corundum, medium-grained	• 125 mils • Cut to size • Heat with propane torch
Preformed Thermoplastic-B (Vendor B)	Embedded corundum, fine-grained	• 125 mils • Cut to size • Heat with propane torch
Epoxy-modified acrylic paint ("System A" polymer chemistry)	Fine-grained corundum	• Mix liquid components • Apply with a smooth foam roller brush • Lightly sprinkle aggregate after each layer • Allow layer to dry and repeat for 5 total layers • Target total of 30 mils wet
Epoxy, 100% solids	Colored crushed glass, medium grained (Used red-colored glass since green was unavailable. Material was not tested for color.)	• Mix liquid components • Apply with v-notched squeegee to 30 mils • Drop aggregate onto epoxy
MMA-A (Vendor A)	Corundum aggregate	• Mix liquid components then mix in aggregate • Apply with v-notched squeegee to 30 mils • Back-roll with a ⅜-inch-nap roller
MMA-C (Vendor C)	Silica sand aggregate, 1 mm	• Mix liquid components then mix in aggregate • Apply with v-notched squeegee to 30 mils • Back-roll with a ⅜-inch-nap roller
Polymer-cement slurry	Small sand and proprietary aggregate	• Add water to ready-mix and mix • Spray applied (drywall sprayer) or squeegeed • Required a surface sealant, but was omitted because the product was not provided

The markings were installed on the following substrates: DGFC (high and low density), OGFC, concrete, and fabricated metal plates. The specific combinations of marking materials and substrates varied for each experiment, as shown in Table 4-3. All GCPMs materials were collected from vendors typically supplying to FDOT. The DGFC and OGFC asphalt mixtures were collected from Florida asphalt plants. The raw concrete components were collected from a concrete plant in Texas.

Table 4-3. GCPM Materials and Substrates by Experiment.

Experiment	GCPM Materials	Substrates
1. Friction and Color with Polishing	• Preformed Thermo.-A • Epoxy-Acrylic • MMA-A • MMA-C • Epoxy/Acrylic • Polymer Cement	• DGFC—96%
2. Accelerated Weathering	• Preformed Thermo.-A • Preformed Thermo.-B • Epoxy-Acrylic • MMA-A • MMA-C • Polymer Cement	• Metal plates
3. Pull-Off Test for Marking, Bond, and Substrate Strength	• Preformed Thermo.-A • Preformed Thermo.-B • Epoxy-Acrylic • MMA-A • MMA-C • Polymer Cement	• DGFC—96% • DGFC—90% • OGFC • Concrete
4. Thermal Compatibility	• Pref. Thermoplastic-A • Epoxy-Acrylic • Epoxy • MMA-A • Polymer Cement	• DGFC—96% • DGFC—90% • OGFC • Concrete

Experiment 1: Friction and Color versus Polishing

Methods

DGFC asphalt slabs (16 inch × 20 inch × 2 inch) were molded and the surfaces sand-blasted. Five GCPM materials were applied to the slabs (Figure 4-1): preformed thermoplastic-A (vendor A), epoxy-acrylic, MMA-A (vendor A), MMA-C (vendor C), and polymer cement slurry. The application was made using the procedures described in Table 4-2.

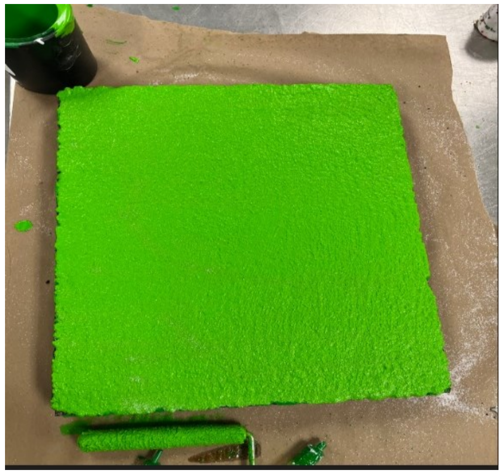


Figure 4-1. GCPM Slab Immediately after Application of MMA.

Initial readings of color and dynamic friction were collected. Next, the research team applied 150,000 cycles in a three-wheel polisher and measured friction and color at 5,000, 20,000, 50,000, 100,000, and 150,000 cycles. Figure 4-2 shows the polisher, DFT, and spectrophotometer used to polish, measure friction, and measure color of the slabs, respectively.

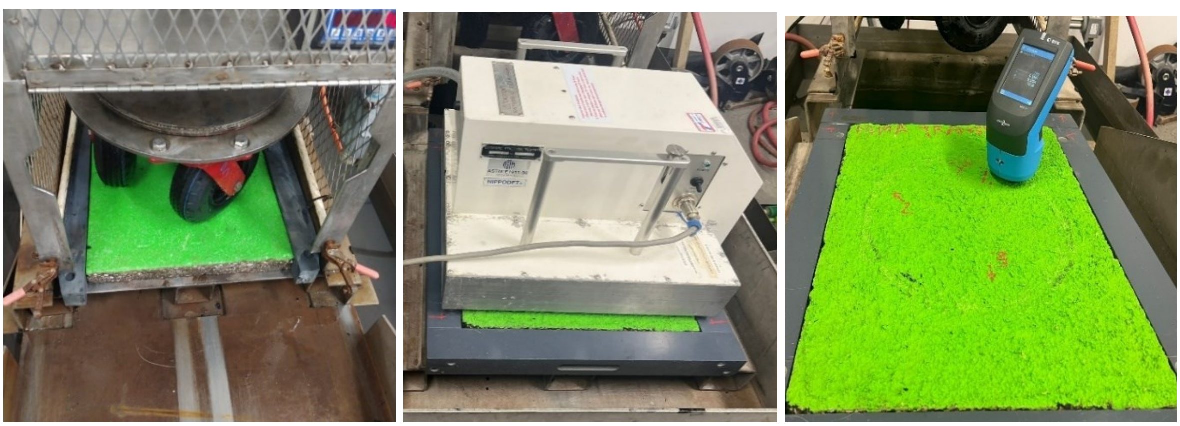


Figure 4-2. NCAT Three-Wheel Polisher, DFT, and BYK Spectrophotometer.

Friction and Wear Results

All the GCPM materials, except the polymer cement, withstood 150,000 cycles with minimal wear (Figure 4-3). The polymer cement sample, however, was polished down to the substrates after just 5,000 cycles, and there was no reason to continue testing the specimen. The polymer cement was cured seven days before testing, which should be sufficient since the treatment can be open to traffic after the day of installation. It may be an indication that the material is not suitable for heavy turning and stop-and-go urban traffic.

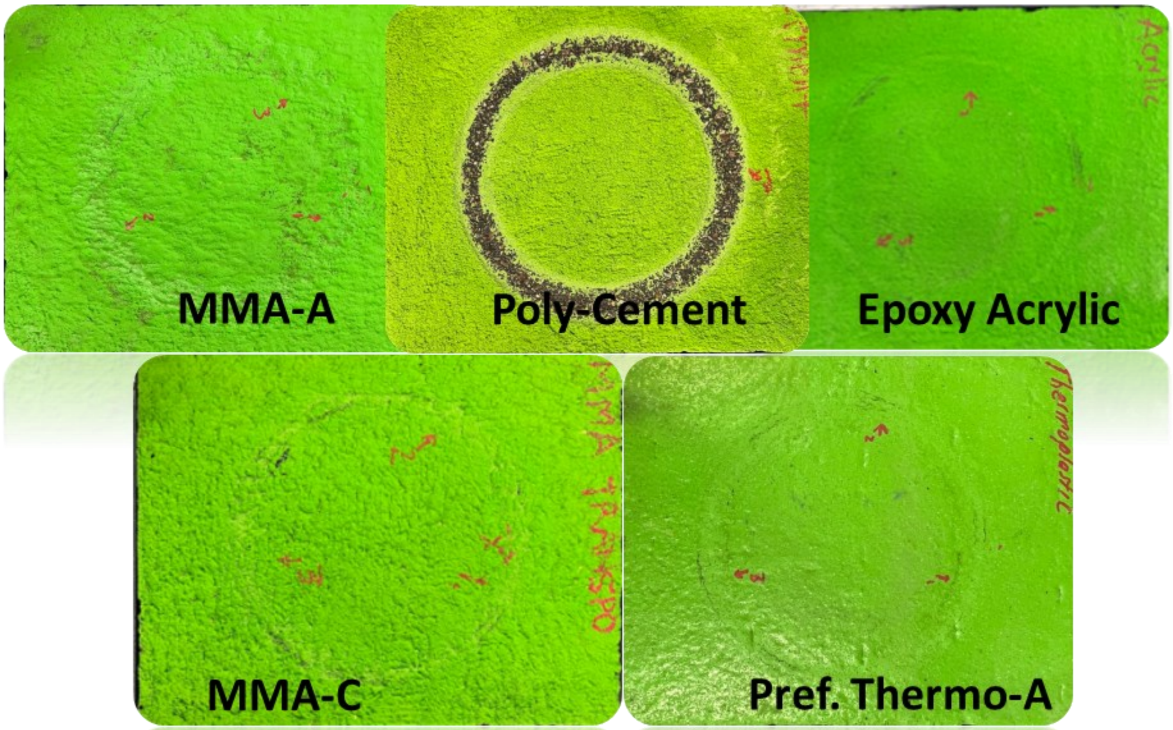


Figure 4-3. All GCPM Polished at 150,00 Cycles Except Polymer Cement at 5,000 Cycles.

Table 4-4 and Figure 4-4 show the friction measurements throughout polishing on each GCPM material. In general, the friction of all materials reduced with increased wheel passes, and after 20,000 cycles, the friction remained relatively constant, with a maximum coefficient of variation of less than 6 percent. Figure 4-4 shows the final coefficient of friction for epoxy-modified acrylic, MMA-C, and preformed thermoplastic fell just above 0.5. In contrast, the final friction for MMA-A hovered just below 0.4.

Table 4-4. Friction of GCPM Materials versus Polishing Cycles.

Cycles	Dynamic friction coefficient, μ at 40km/h				
	Pref. Thermoplastic-A	Epoxy-Acrylic	MMA-A	MMA-C	Poly. Cement
0	0.72	0.84	0.405	0.8	0.595
5,000	0.63	0.55	0.355	0.595	0.435
20,000	0.575	0.535	0.39	0.53	None
50,000	0.515	0.57	0.38	0.59	None
100,000	0.52	0.53	0.39	0.515	None
150,000	0.515	0.503	0.36	0.525	None

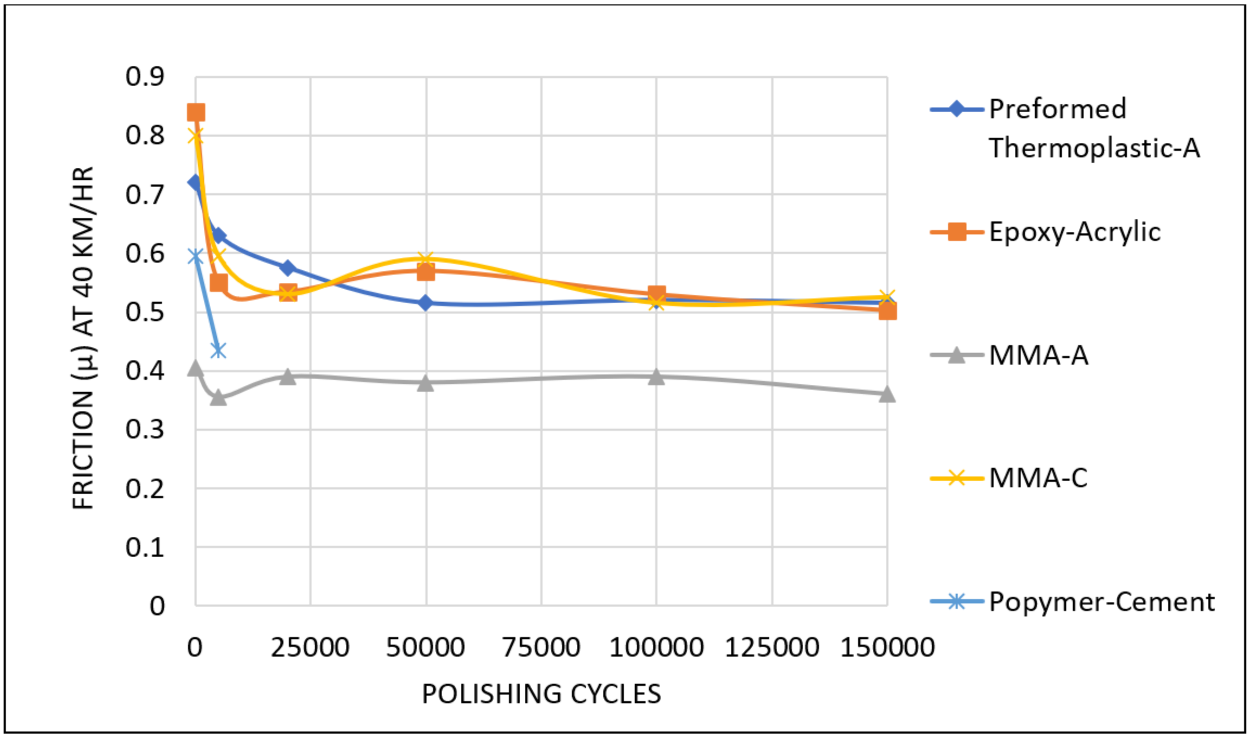


Figure 4-4. Friction versus Polishing Cycles.

Regarding percentage friction drop, only about 15 percent drop was observed between 50,000 and 150,000 cycles. If the departments of transportation (DOTs) sought to optimize testing efforts, they could use this fact to their advantage. Testing could be done up to 50,000 cycles, and if the friction value was 0.6 or higher, they could stop the test early knowing that there is very little chance the value could drop to 0.5 or lower beyond that point.

Color Results

Except for the polymer cement, all other materials withstood the 150,000 cycles without dropping out of the color box. As recommended by FDOT, the luminance (Y) was above 15 for all materials before and after polishing. Table 4-5 and Table 4-6 show the chromaticity (x-y) color coordinates and the luminance (Y) of the tested GCPMs at different polishing cycles respectively. In addition, Figure 4-5 show the measured chromaticity color coordinates superimposed on the color box. The point outside the color box is from testing the substrate after the polymer cement was worn away.

Table 4-5. Chromaticity of GCPM Materials versus Polishing Cycles.

Polishing Cycles	Color Coordinates (x,y)				
	Pref. Thermo.-B	Epoxy-Acrylic	MMA-A	MMA-C	Poly. Cement
Initial	0.324, 0.540	0.325, 0.531	0.310, 0.501	0.330, 0.533	0.352, 0.491
5,000	0.324, 0.510	0.323, 0.540	0.310, 0.492	0.329, 0.523	0.339, 0.385
20,000	0.323, 0.515	0.324, 0.540	0.310, 0.499	0.331, 0.524	-
50,000	0.325, 0.512	0.323, 0.544	0.310, 0.491	0.331, 0.508	-
100,000	0.323, 0.515	0.323, 0.533	0.309, 0.490	0.330, 0.513	-
150,000	0.324, 0.513	0.324, 0.533	0.312, 0.485	0.329, 0.505	-

Table 4-6. Luminance of GCPM Materials versus Polishing Cycles.

Polishing Cycles	Luminance (Y)				
	Pref. Thermo.-B	Epoxy-Acrylic	MMA-A	MMA-C	Polymer Cement
Initial	29.8	20.6	25.5	19.5	32.1
5k	30.9	21.5	25.3	18.9	11.6
20k	31.2	20.8	24.2	21.2	-
50k	28.9	20.8	25.2	25.7	-
100k	30.2	21.1	25.4	21.6	-
150k	31.1	20.5	24.0	21.5	-

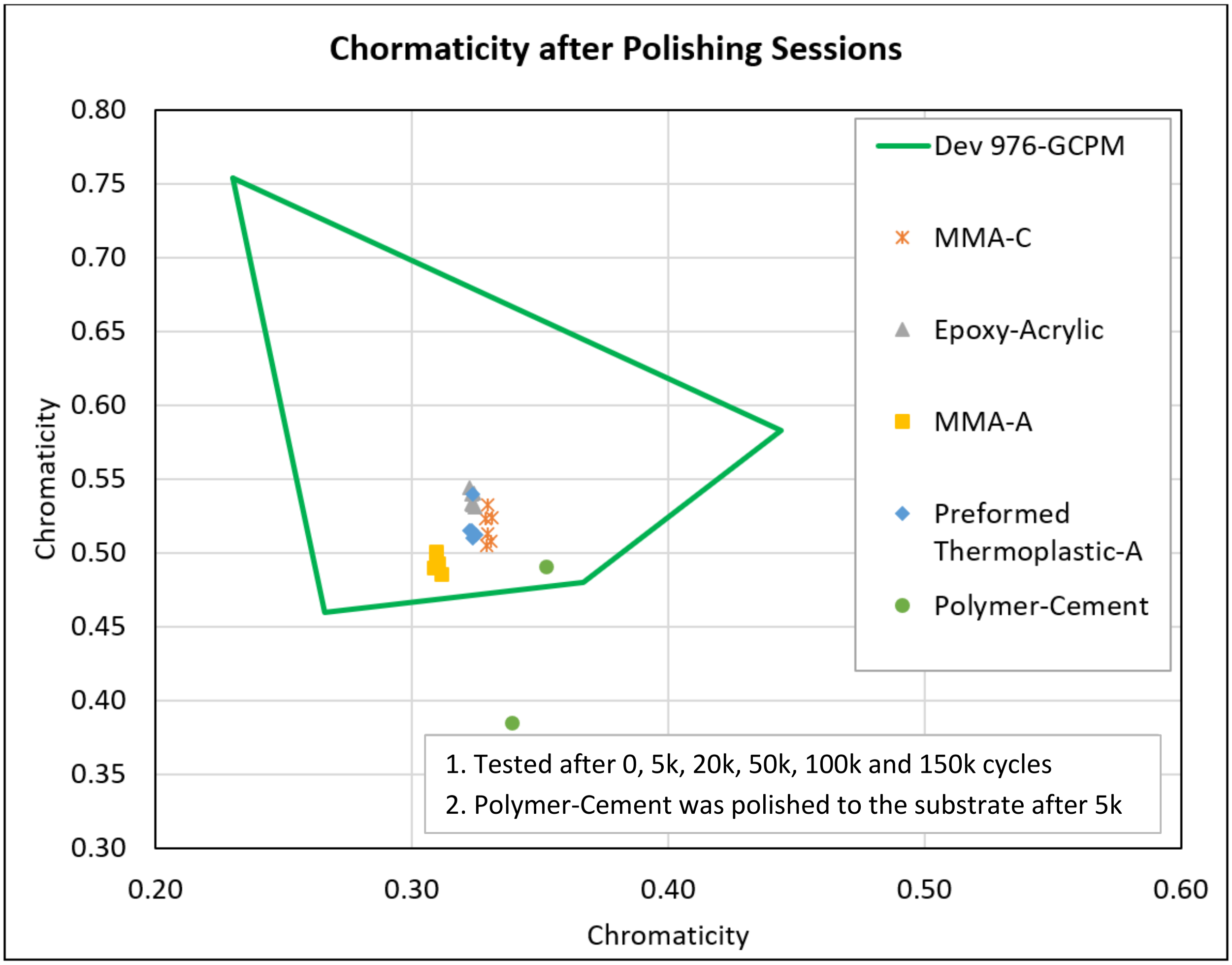


Figure 4-5. Chromaticity versus Polishing Cycles.

Experiment 2: Accelerated Weathering

Methods

A Q-Sun XE-3 Xenon Test Chamber (Figure 4-6) was used to simulate GCPM materials' direct exposure to solar radiation, heat, and moisture. The Q-Sun device can weather 12 specimens simultaneously. The spectral power distribution of the filtered xenon arc conforms to Section 6.1.3 Spectral Irradiance of Xenon Arc with Daylight Filters in ASTM G155 (Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials) (ASTM, 2013).

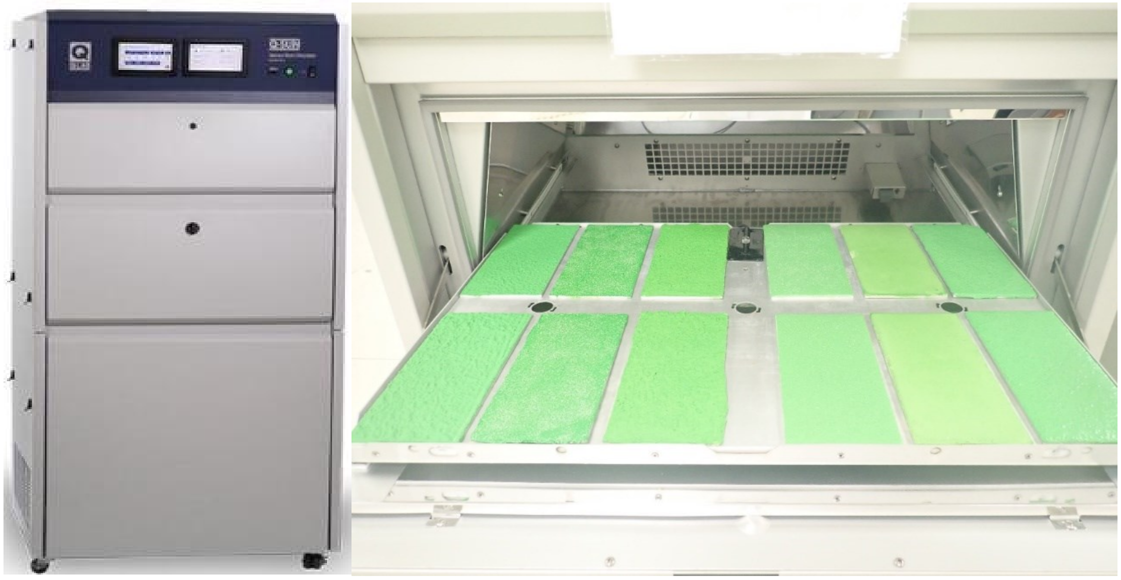


Figure 4-6. Q-Sun XE-3 Xenon Test Chamber.

The research team prepared duplicate GCPM samples of the following materials: preformed thermoplastic-A, preformed thermoplastic-B, epoxy-modified acrylic, MMA-A, MMA-B, and polymer cement. The substrates were 4-inch × 8-inch × ⅛-inch aluminum plates, roughened and cleaned to enhance bonding. Materials were applied according to the manufacturer's instructions (see Table 4-2). Sample preparation for preformed thermoplastic and MMA is shown in Figure 4-7.

Figure 4-7. Preformed Thermoplastic and MMA Weathering Specimen Preparation.

The samples were tested with the Q-Sun XE-3 for 1,000 exposures hours at the FDOT State Materials Office laboratory. The exposure parameters are shown in Table 4-7 and include cycles of water spray. Continuous light was chosen to accelerate the test as much as possible. The full test simulates six months of exposure in Miami, FL (see Appendix D). Before exposure, and after 100, 250, 500, and 1,000 exposure hours, the chromaticity (x, y) and luminance (Y) of each sample were measured with a BYK spectro2guide spectrophotometer. The spectrophotometer test specifications are shown in Table 4-8.

Table 4-7. Weatherometer Exposure Parameters.

Parameter	Value
Irradiance Set at 340 nm	0.51 w/(m^2 nm)
Light/Dark	Continuous light
Uninsulated Black Panel Temperature Set Point	63°C
Water Spray Cycle	102 minutes no spray 18 minutes water spray
Relative Humidity	50% during light only
Total Exposure Hours	1000

Table 4-8. Spectrophotometer Test Parameters.

Parameter	Value
Geometry	45°c:0° system
Light Source Illuminance	D65
Observation Angle	2°

Color Degradation Results

The GCPM specimens before and after 1,000 exposure hours are shown in Figure 4-8. The red "X" indicates samples that do not comply with the color requirements after weathering. The average chromaticity (x, y) coordinates and luminance (Y) are shown in Table 4-9 and Table 4-10, respectively. In addition, the research team plotted the chromaticity (x, y) coordinates against the standard FHWA color box to observe if the material's color excessively faded (Figure 4-9). The materials are deemed to fade color if the coordinates fall off the box. For example, close observation of the data shows that the cementitious material (P-CM) fell off the color box below 98 hrs of exposure. Similarly, a thermoplastic material (C-TP) fell off the color box below 250 hrs of exposure.

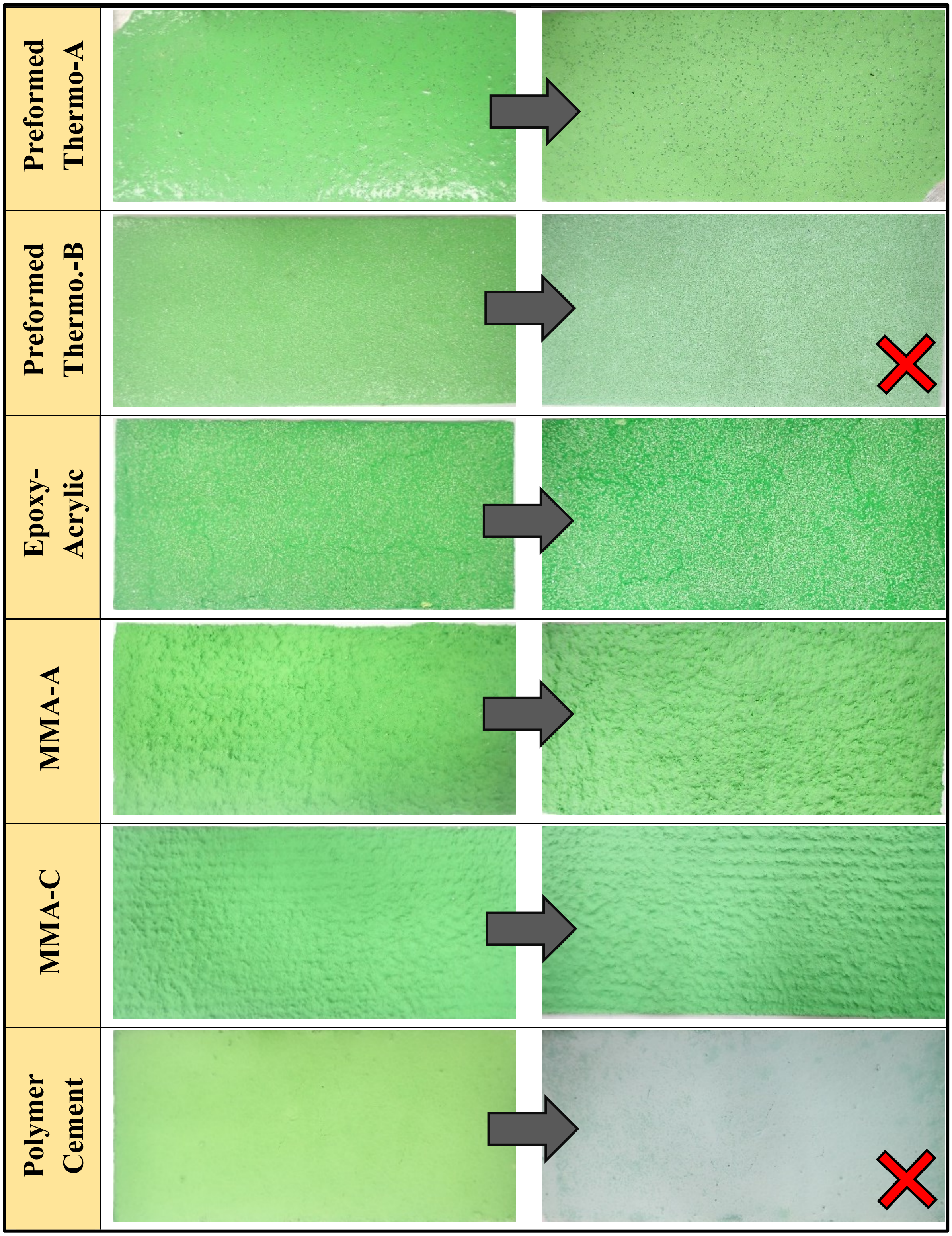


Figure 4-8. GCPM Specimens before and after 1,000 Hours of Weatherometer Exposure.

Table 4-9. Color Coordinates of GCPM Materials versus Weathering.

Exposure Hours	Average Chromaticity Color Coordinates (x, y)					
	Preformed Thermo.-A	Preformed Thermo.-B	Epoxy-Acrylic	MMA-A	MMA-C	Polymer Cement
0	0.32, 0.54	0.33, 0.49	0.31, 0.50	0.33, 0.54	0.31, 0.50	0.34, 0.51
98	0.32, 0.54	0.33, 0.48	0.32, 0.49	0.33, 0.53	0.31, 0.49	0.33, 0.46
250	0.33, 0.51	0.32, 0.45	0.32, 0.48	0.33, 0.53	0.31, 0.49	0.31, 0.39
500	0.33, 0.50	0.32, 0.43	0.31, 0.49	0.33, 0.52	0.31, 0.48	0.30, 0.36
1,000	0.34, 0.51	0.32, 0.43	0.31, 0.48	0.32, 0.50	0.31, 0.47	0.29, 0.35

Table 4-10. Luminance of GCPM Materials versus Weathering.

Exposure Hours	Average Luminance (Y)					
	Preformed Thermo.-A	Preformed Thermo.-B	Epoxy-Acrylic	MMA-A	MMA-C	Polymer Cement
0	30.4	30.7	23.1	23.4	26.3	34.4
98	31.9	31.6	23.7	24.6	25.9	33.7
250	35.2	35.4	23.9	25.6	26.8	41.0
500	37.0	37.2	23.4	25.7	27.5	49.6
1,000	33.1	35.4	21.9	25.9	28.0	54.2

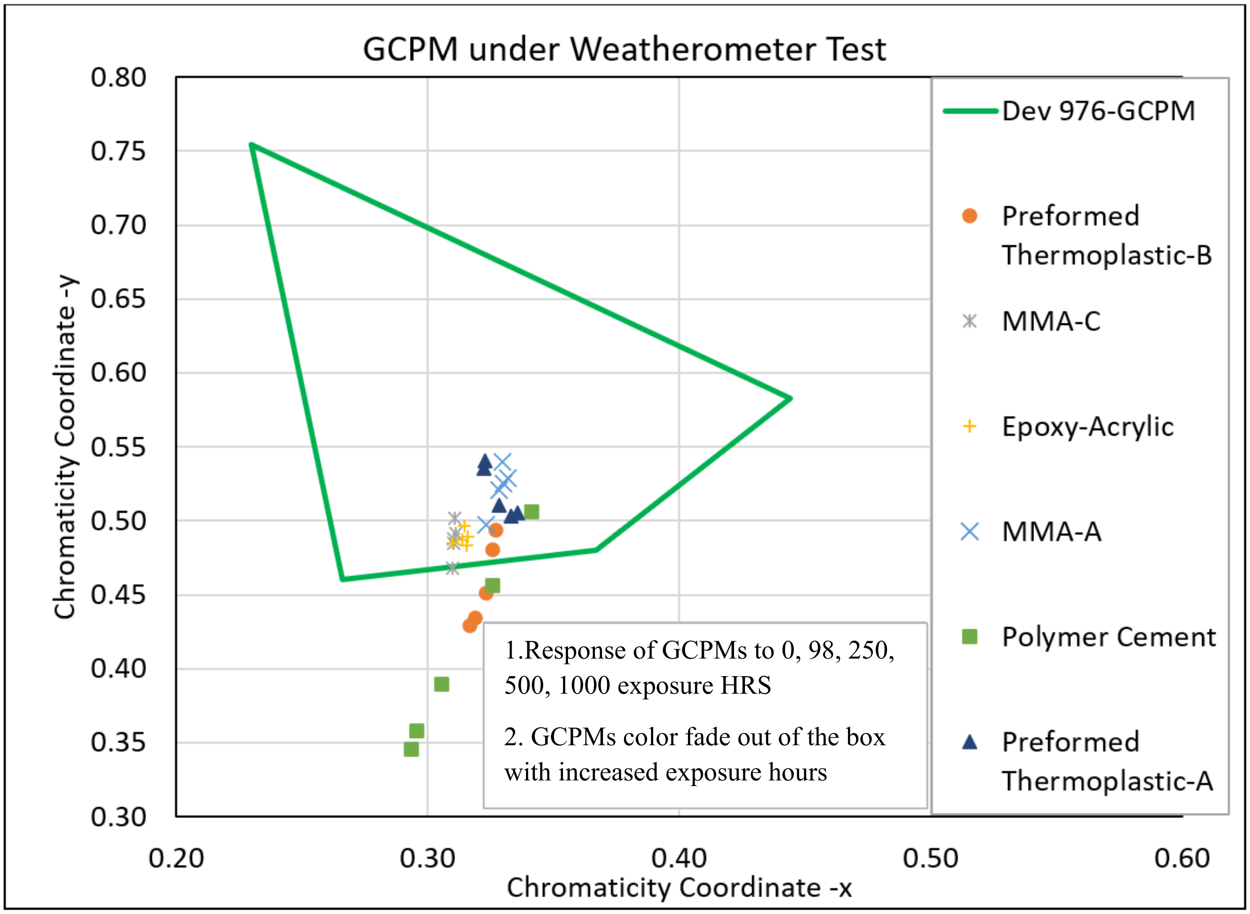


Figure 4-9. GCPMs Chromaticity at 0, 98, 250, 500, 1000 Hours in Weatherometer.

From Figure 4-5 above, the research team deduced that changes in chromaticity were most evident along the y-coordinate. Also, the values were not near the left-most boundary in the x-coordinate. Therefore, the researchers plotted the chromaticity y-coordinate versus exposure time to estimate when the GCPM color left the color box (Figure 4-10). Using the minimum y-coordinate threshold of 0.46, the researchers proposed a reduced testing duration of 240 hours. Previously, the AASHTO Taskforce proposed 144 hours to weather the GCPMs artificially. The AASHTO Taskforce used ASTM G155 (AASHTO, 2019), whereas, in this research, the ASTM D4956 method was used. In selecting the minimum exposure hours, the research team considered the following reasons:

- The failed GCPMs disappeared from the color box after about 200 weatherometer exposure hours. The research team established 200 hours as the theoretical minimum exposure hours needed to weather the GCPMs. Therefore, for practical purposes, the actual value should be higher than the theoretical value.
- Considering that the data set is relatively small, the research team assumed a reliability of 80 percent. The reliability pushed the minimum exposure time to about 240 hours. Also, for convenience, 240 hours is exactly ten days of testing.

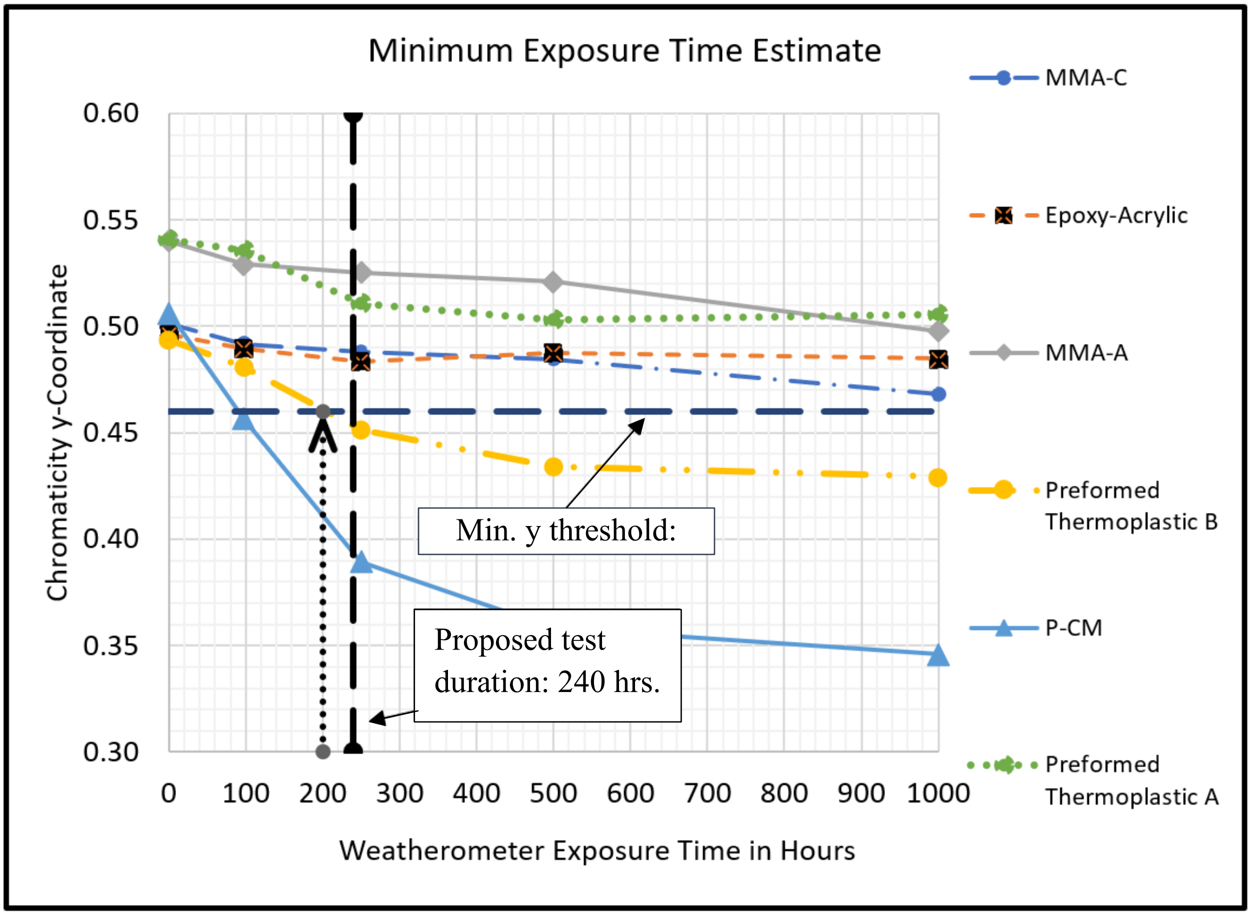


Figure 4-10. Estimating Working Exposure Hours.

Experiment 3: Pull-Off Test for Marking, Bond, and Substrate Strength

Method

The pull-off test and procedure are well-documented in Chapter 3 when evaluating the field cores in the laboratory. In summary, a circular cut is made using a barrel drill bit through the marking but not completely through the sample. A metal disk is attached to the remaining sample. Then a direct-tensile force is applied to the disks using the pull-off device until failure. Usually, the cut extends deep into the specimen; however, in this study, the research team went with shallow grooves of less than ⅛ inch so the sample was more likely to fail at the bond.

The research team compacted cylindrical specimens with a gyratory compactor to varying densities as substrates for the GCPM materials (Figure 4-10). Substrates included DGFC at 96 percent density, DGFC at 90 percent density, and OGFC at 80 percent density. The team applied the following GCPM materials to the substrates: preformed thermoplastic-A, preformed thermoplastic-B, epoxy-acrylic, MMA-A, MMA-C, and polymer cement. Samples before and after the marking are shown in Figure 4-11.

Figure 4-11. Example of Sample Preparation for Pull-Off Test.

Pull-Off Test Results

Every sample except the polymer cement failed near the bond interface and had pieces of substrate aggregate attached (Figure 4-12). The preformed thermoplastic on OGFC peeled off with few aggregates because it has less surface area to hold. The polymer cement, however, failed within the GCPM. Table 4-11, Figure 4-13, and Figure 4-14 show the average pull-off strength values for different GCPMs on different substrates. The values indicate that the OGFC is the weakest substrate, as was observed in the field study. The highest substrate strength was observed on high-density DGFC. On average, the epoxy modified acrylic GCPM offered the highest bond strength.

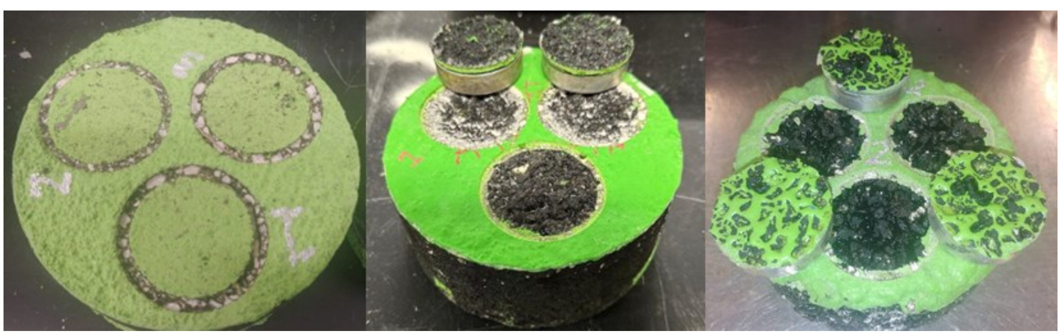


Figure 4-12. Pull-Off Test Mode of Failure.

Table 4-11. Average Pull-Off Strength (psi) Result by Substrate and GCPM Material Type.

GCPM Type	Pull-Off Strength (psi)				CV (%)
	DGFC (96% density)	DGFC (90% density)	OGFC (80% density)	Average	
Pref. Thermo-A	140	140	72	117	27.5
Pref. Thermo-B	132	99	85	105	18.7
Epoxy-Acrylic	191	180	140	170	12.9
MMA-A	129	131	99	120	12.0
MMA-C	147	122	124	131	8.6
Poly. Cement	138	97	120	118	14.2
Average	146	128	107		
CV (%)	14.2	21.9	22.1		

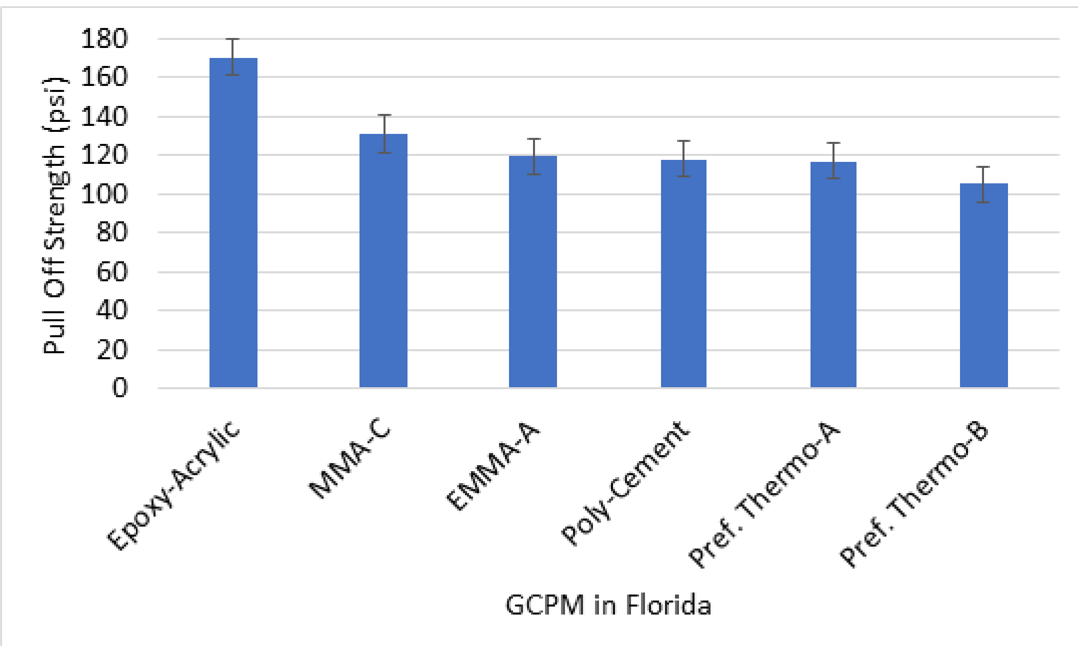


Figure 4-13. Average Pull-Off Strength of GCPM on All Substrate Types.

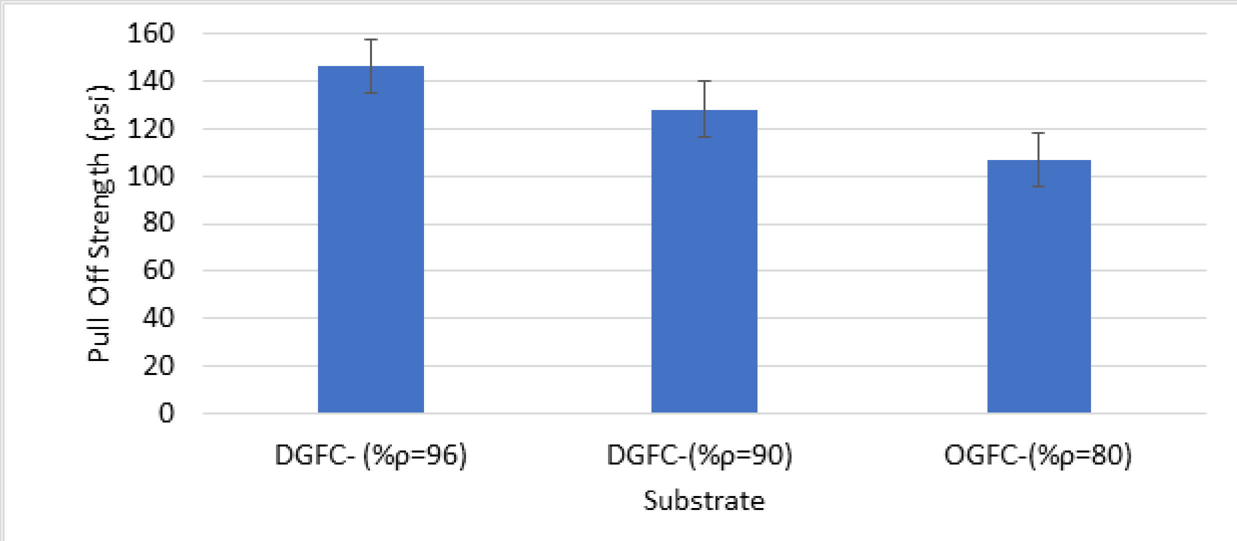


Figure 4-14. Average Pull-Off Strength on Different GCPM Substrates.

Experiment 4: Thermal Compatibility

Method

Thermal compatibility was evaluated using a modified ASTM C884 (Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay). In the standard, a concrete substrate is overlaid with 0.5 inches of epoxy mortar, and the sample is subjected to five 24-hour freeze-thaw cycles. Any signs of cracking at the bond interface, within the substrate, or within the mortar denotes thermal incompatibility. The test does not, however, test for the thermally induced failure of weaker substrates like asphalt concrete.

The test was modified to include different asphalt concrete substrates (i.e., DGFC—96 percent density, DGFC—90 percent, and OGFC—80 percent), different treatment types (i.e., preformed thermoplastic-A, epoxy-acrylic, epoxy, MMA-A, and polymer cement), and application thicknesses (i.e., 0.5 inches and the treatment design thickness). The sample combinations tested are shown in Table 4-12. The focus was on the two most popular treatments, epoxy-modified acrylic and thermoplastic. These were tested at the standard 0.5-inch thickness and the treatment design thicknesses. The other materials were only tested at 0.5-inch thickness since this thicker configuration had the highest possibility of indicating failure.

Table 4-12. Thermal Compatibility Test Matrix.

Substrate	Preformed Thermo.-A		Epoxy-Acrylic		Epoxy	MMA-A	Polymer-Cement	None
	Design	0.5-in.	Design	0.5-in.	0.5-inch	0.5-inch	0.5-inch	
Concrete	NA	X	NA	X	X	X	X	X
DGFC (Low Voids)	X	X	X	X	X	X	X	X
DGFC (High Voids)	X	X	X	X	X	X	X	X
OGFC	X	X	X	X	X	X	X	X

All the slabs were 12 inches square and 3 inches thick. The concrete slabs were fabricated in square molds and then cured at 100 percent humidity for a minimum of 28 days. The asphalt slabs were molded using a laboratory slab compactor. The actual air voids for the DGFC-low slabs were 8.8 percent and for DGFC-high were 10.1 percent. The surfaces of the slabs were prepared with industrial sandblasting to expose the coarse aggregate and promote better treatment adhesion (Figure 4-15). The epoxy concrete surface was prepared with a diamond grinding wheel.

Figure 4-15. Sandblasting and Prepared Slab Surfaces.

The treatments were generally prepared and applied according to the manufacturers' recommendations, with exceptions for the 0.5-inch-thick applications. The epoxy-modified acrylic treatment was built up with over 50 layers and was dried with a heat gun between layers. Without accelerated drying, sample preparation would have been unacceptably time-consuming. The preformed thermoplastic was applied in five layers to achieve 0.5 inches. The epoxy, MMA, and polymer cement were poured onto the slabs secured in a 0.5-inch-high wooden mold around the edges. The team noted that these thick layers were more susceptible to segregation. On OGFC, some of the epoxy treatment drained down into the void structure. In addition, the coarse aggregate in the polymer cement samples tended to sink rather than stay in suspension, which added variation between samples. For example, out of multiple samples from the same batch, one of the samples had a higher water content when pouring. Figure 4-16 shows the application of each GCPM treatment. The epoxy treatment was red because the vendor only had red-dyed aggregate available at the time but is otherwise identical to the standard green bike lane (GBL) epoxy treatment.

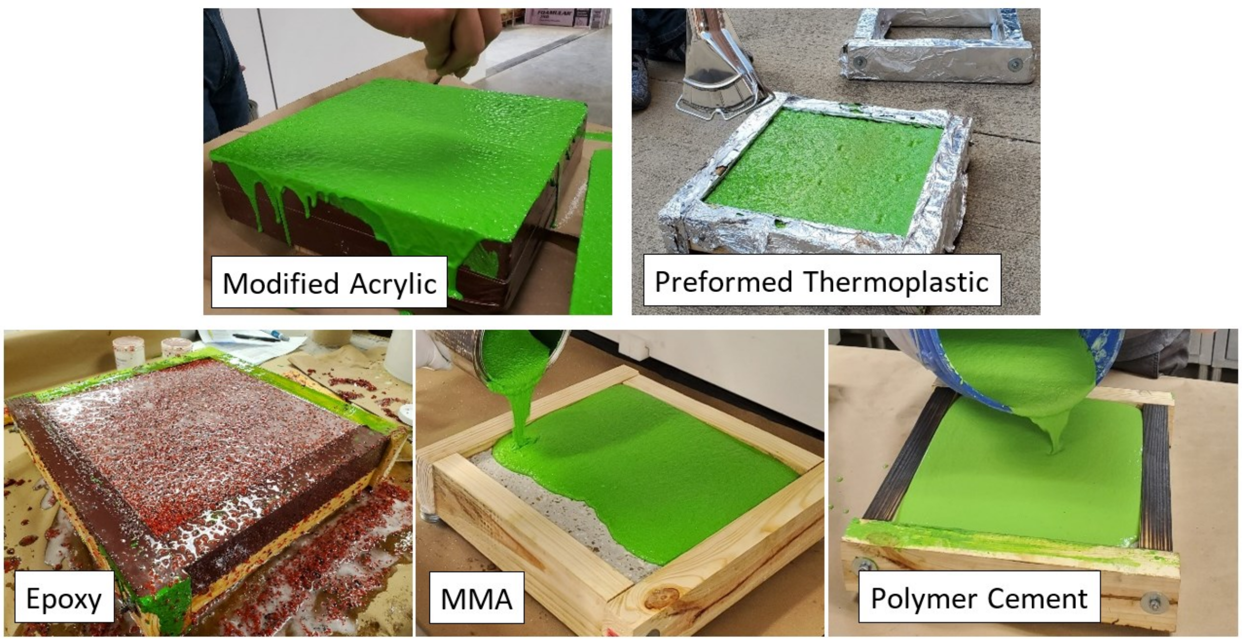


Figure 4-16. Treatment Application.

The condition of each slab was thoroughly documented before and after freeze-thaw conditioning. Then, triplicate pull-off tests were done on each slab to provide a quantifiable measure of the sample condition. In this study, the pull-off test locations were cut through the treatment and two inches into the substrate (Figure 4-17). The pull-off results from the slabs with the GCPM treatments were compared to the pull-off strengths of the control slabs to evaluate if the treatment caused any damage, even if visible distress was not present.

Figure 4-17. Pull-Off Test on Slabs after Freeze-Thaw.

Cracking Results

Figure 4-18 shows examples of the slabs after freeze and thaw conditioning. The full cracking results are in Table 4-13. The research team observed that one concrete slab treated with 0.5-inch MMA had thermal-induced cracking. The only other signs of distress were from the sample preparation. The polymer-cement slab on concrete had shrinkage cracking on the surface. This treatment on this sample, notably, had a higher water content because of mixture segregation. The thick modified-acrylic samples also had shrinkage cracks on the surface (Figure 4-19). The cracks were induced by curing the water-based treatment quickly with a heat gun.

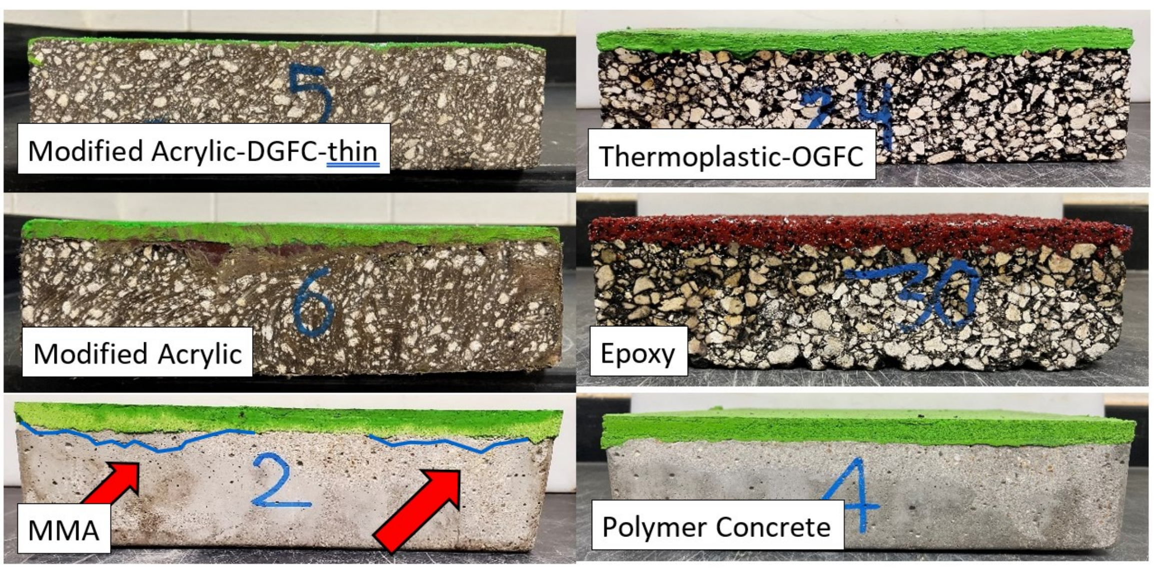


Figure 4-18. Samples after Freeze-Thaw.

Table 4-13. Visual Thermal Compatibility Failure.

Substrate	Epoxy-Acrylic		Thermoplastic		Epoxy	MMA	Polymer-Cement
	Design	0.5-in.	Design	0.5-in.	0.5-in.	0.5-inch	0.5-inch
Concrete	No test	N	No test	N	N	Failure	N
DGFC (Low Voids)	N	N	N	N	N	N	N
DGFC (High Voids)	N	N	N	N	N	No test	No test
OGFC	N	N	N	N	N	N	N

[N] - No break.

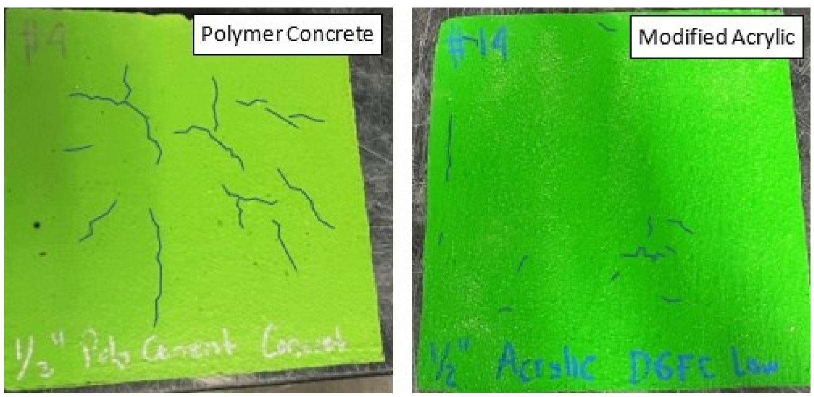


Figure 4-19. Shrinkage Cracking after Surface Preparation (Cracks Enhanced).

Pull-Off Strength Results

The average bond strength results after freeze-thaw conditioning are shown in Table 4-14. The table also shows the failure location and the strength ratio, which is the pull-off strength of the sample conditioned with a treatment divided by the control (no treatment on the substrate). The strength ratio indicates if the substrate was damaged after freeze-thaw conditioning because of a thermally incompatible treatment. Calculating the strength ratio is not meaningful if the failure mode was anywhere but the substrate.

Table 4-14. Thermally Stressed Pull-Off Strength Results.

Substrate	Pull-Off Strength, psi (Strength Ratio, %) * [Failure Location]							
	Thermo.-A, Design	Thermo.-A, 0.5-in.	Epx-Acryl, Design	Epx-Acryl, 0.5-in.	Epoxy, 0.5-in.	MMA-A, 0.5-in.	P-Cement, 0.5-in.	None
Concrete	No test	126 (NA) [G]	No test	196 (NA) [B]	439 (NA) [N]	212 (0.5) [B] [S]	192 (NA) [B]	429 [N]
DGFC (Low Voids)	180 (1.2) [S]	150 (NA) [G]	154 (NA) [B]	118 (0.8) [S]	167 (1.1) [S]	142 (0.9) [S]	141 (0.9) [S]	155 [S]
DGFC (High Voids)	151 (1.2) [S]	161 (1.3) [S]	143 (1.2) [S]	163 (1.3) [S]	146 (1.2) [S]	No test	No test	125 [S]
OGFC	69 (1.1) [S]	73 (1.2) [S]	67 (1.1) [S]	58 (0.9) [S]	168 (2.8) [S]	75 (1.2) [S]	65 (1.1) [S]	61 [S]

**Strength with treatment/strength without treatment (substrate failure only).*
[G] – GBL [B] – Bond [S] - Substrate [N] - No break.

The strength data were statistically analyzed to identify trends between substrate type, treatment type, and treatment thickness. The analysis results, using a subset of data that only includes 0.5-inch-thick treatments, are shown in Figure 4-20. The strength was highest on concrete, where failure generally occurred at the bond. Thermoplastic broke between the multiple applied layers, and the epoxy sample did not break. The dense grade was next, typically breaking within the substrate, and OGFC was weakest. On average, most treatments had pull-off strengths between 120 and 150 psi. However, on average, the epoxy treatment had a much higher strength of 250 psi. This is because the epoxy bonded very well to the concrete, and when making the OGFC sample, the epoxy had a significant drain-down into the substrate, which increased the substrate strength. The strength ratios show that the thermal stresses damaged the concrete because the ratio is substantially lower than 1.0. Only one concrete sample failed in the substrate: the MMA slab. The OGFC samples were stronger with the treatment applied, especially for the epoxy sample. On average, the polymer-cement treatment weakened the substrates the most compared to the control.

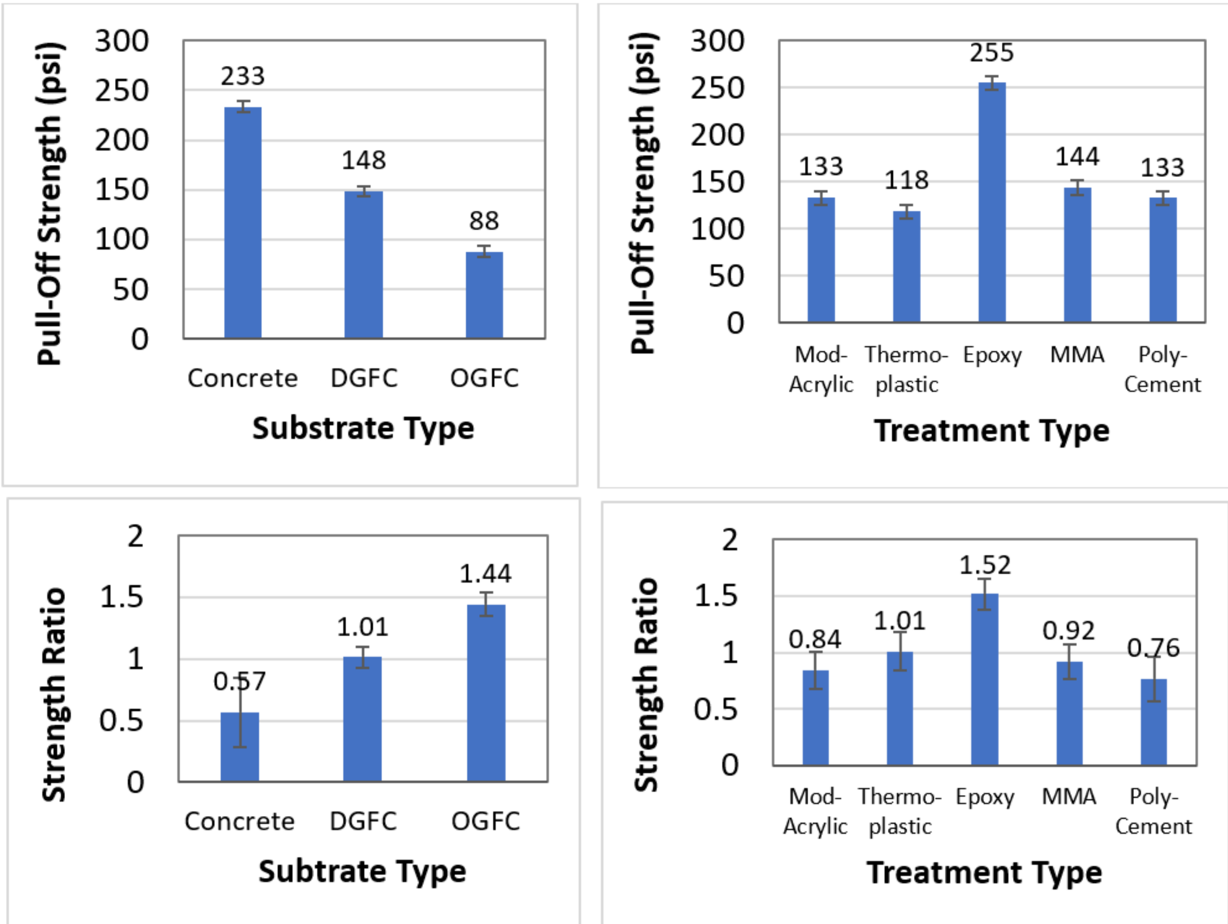


Figure 4-20. Pull-Off Strength and Strength Ratio after Freeze-Thaw Conditioning (All Treatments, 0.5 Inches Thick).

The results focusing on the epoxy-acrylic and preformed thermoplastic-A treatments are shown in Figure 4-21. In this data set, both high void and low void DGFC were evaluated, but the difference between the two was not statistically significant. The concrete was slightly stronger, and the OGFC was weakest. The strength of both treatments was around 130 and 140 psi. The effect of treatment thickness was, surprisingly, not significant. Strength ratios were all greater than 1.0, meaning that thermal stress induced by applying an upper treatment did not measurably affect the substrate condition. Strength ratio data for concrete were unavailable since none of the samples with treatment broke in the substrate.

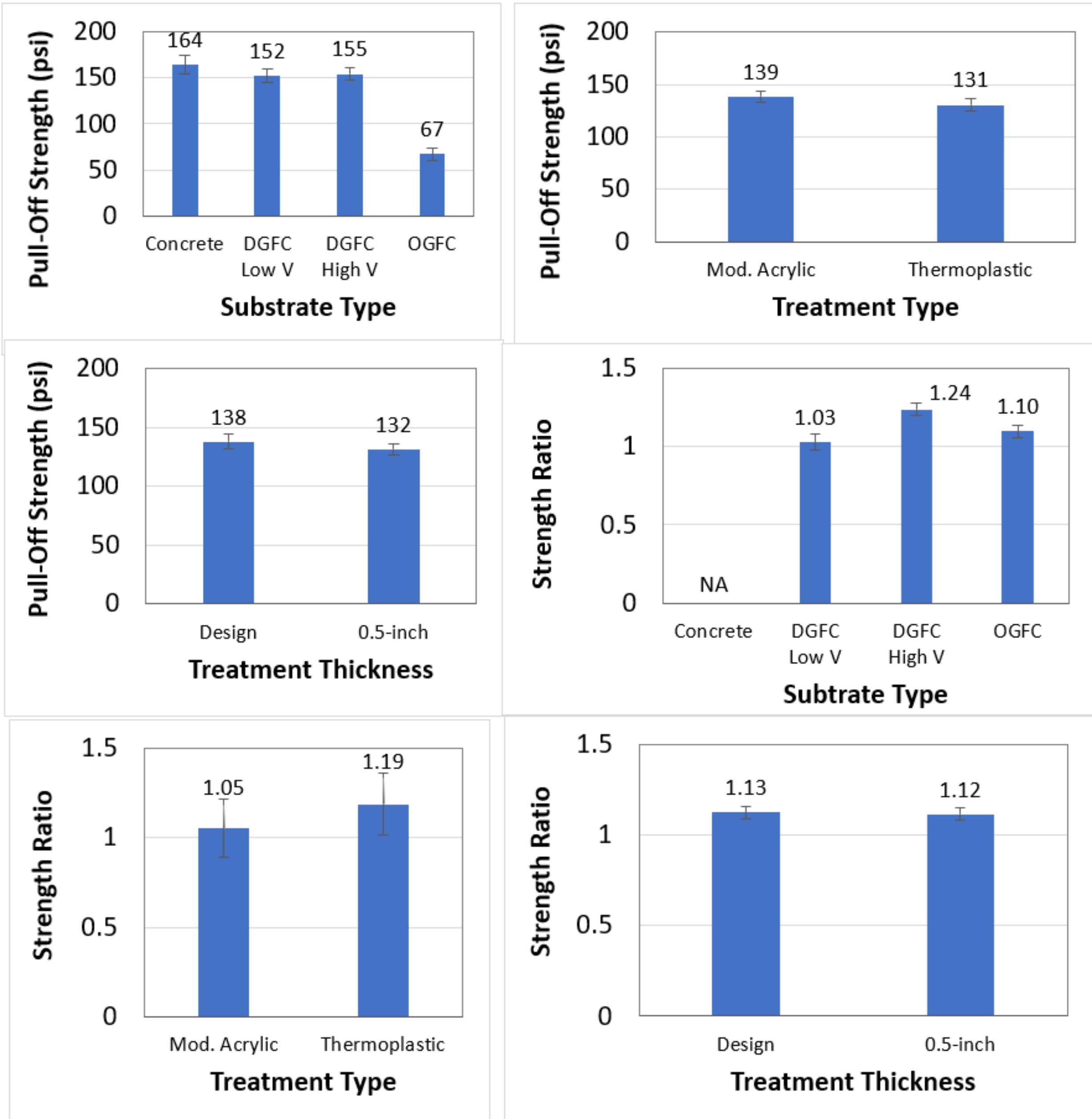


Figure 4-21. Pull-Off Strength and Strength Ratio after Freeze-Thaw Conditioning (Modified Acrylic and Thermoplastic; Design Thickness and 0.5 Inches Thick).

CHAPTER 5
CONCLUSION

The conclusions of the work herein are based on a literature review, a survey of industry personnel, an inspection of Florida GPCM sites, and laboratory testing to supplement the field observations.

In the field, the research team documented the performance of 30 GCPM installations. They identified the probable failure mechanisms and causes of each observed distress. The sites represented five material types: preformed thermoplastic (12 sites), epoxy-modified acrylic (13 sites), epoxy resin (1 site), MMA (3 sites), and nondurable paint (1 site).

In the laboratory, four experiments were conducted to address different research questions:

1. Evaluate the friction and color performance with polishing of GCPM materials
2. Assess an accelerated weathering test to prequalify GCPM materials
3. Validate field observations of debonding and substrate failure
4. Assess a thermal compatibility test to prequalify GCPM materials.

The GCPM materials tested were preformed thermoplastic (from two vendors), epoxy-modified acrylic, epoxy resin, MMA (from two vendors), and polymer-cement slurry. The experiments used a variety of substrate types: DGFC at high and low density, OGFC, concrete, and fabricated metal plates.

This chapter provides the key findings, recommendations, and an implementation plan.

Findings

The research outcomes of the field study, literature review, and interviews were:

- The top three observed distresses were thermal cracking, delamination, and wear. Concerning color, nearly all sites fell outside the chromaticity box, but dramatic discoloration was only observed on a couple sites.
- The thermoplastic sites generally performed well, except on a few sites with delamination. The most dramatic failures were with the epoxy-modified acrylic, which had substantial thermal and moisture-related cracking. The one epoxy resin site had significant loss of glass aggregate and discoloration. The MMA and the nondurable paint site had significant traffic wear.
- Failure causes ranged from poor installation (excessive application thickness), moisture movements (especially near gutters), shrinkage, thermal compatibility, UV exposure, and

traffic conflicts. The specific formulation of epoxy-modified acrylic used on several sites was especially susceptible to shrinkage and moisture absorption.

- Poor or unsuitable substrate could have contributed to some of the cracking and delamination failures. The research team noted that all GCPM installations performed poorly on OGFC. One site on low-density DGFC (AV > 10 percent) also had a failure.
- Based on interviews with green bike lane stakeholders, the research team documented best practices for the installation of GCPMs (i.e., surface preparation, material handling, etc.).

The findings of the laboratory experiments were:

- After 150,000 three-wheel polisher cycles, the color of the GCPM materials was minimally affected, except for the polymer-cement material, which wore away after 5,000 cycles.
- The friction values after 150,000 cycles for thermoplastic, epoxy-acrylic, and MMA-C were all nearly 0.5. While none fell below the 0.5 criterion, statistical variation would have caused other samples of the same materials to fail. The friction of MMA-A was below 0.4.
- GCPM materials exhibited a relatively constant friction level after 20,000 three-wheel polisher cycles.
- The accelerated weathering test successfully differentiated between materials with and without color fastness. The polymer cement and thermoplastic-B materials fell outside the chromaticity box after weathering. GCPM materials that failed after 1,000 exposure hours also failed after less than 250 hours.
- The pull-off test validated the field observation that the substrate strength decreases as density increases.
- The thermal compatibility test was largely ineffective. Out of 24 samples, only one showed signs of thermally induced damage. The test, otherwise, failed to measure the thermal behaviors of the several GCPM materials, application thicknesses, and substrates. The test was also demanding in terms of materials and labor.

Recommendations

- Clearly define the differences between two reactive component systems with high solids contents (e.g., epoxy resin and MMA) and durable paint systems that include reactive components (epoxy-acrylic). These systems have very different material properties, application methods, and performance characteristics. For example, several of the field performance issues with epoxy-acrylic are partly a misunderstanding that the material is not epoxy-resin and is more prone to shrinkage. If epoxy-acrylic must be used, avoid thick and squeegee applications, avoid accelerated curing, and install at locations with lower traffic conflicts.

- Consider lowering the friction requirement to a DFT40 value of 40 ($\mu = 0.4$). The current value of 50 is conservative and nearly disqualified three products currently used in Florida. This also aligns with the friction requirement in Section 974 for patterned pavement materials. Disregard this recommendation if there are data indicating that the higher friction value improves bicycle or driver safety.
- Consider an expedited friction test method where the friction is measured after only 50,000 polisher cycles. If the DFT40 value is greater than 50, the material passes. If it is less than 40, the material fails. Otherwise, polishing will proceed to 150,000 polisher cycles, followed by friction testing. This is not implemented in the specification.
- Suggest that FDOT can check the in-place air-voids of asphalt before applying GCPMs. An air void content ≤ 8 percent may limit moisture from migrating under the marking and reduce substrate failures. This is not recommended for implementation in a specification but is included in the guidelines.
- The modified ASTM C884 method is not recommended for testing the thermal compatibility of GCPM materials. Therefore, the research team does not propose any thermal compatibility test. However, if thermal compatibility is an ongoing issue, consider a flexibility requirement in the materials properties for two component reactive systems.
- Develop and implement a curl test to determine the shrinkage potential of liquid coatings. This simple method could screen the previous generation of epoxy-acrylic paint products, which were prone to shrinkage and performed poorly in several field applications.

The research team used the gathered data to revise the FDOT specifications and test methods, and to develop guidelines. These are discussed in detail in the following subsections.

Dev Section 714—Green-Colored Pavement Markings

- GCPM applications on OGFC are not recommended, and must first be approved by the State Materials Office.
- For preformed thermoplastic, ensure that mechanical blasting or abrading and subsequent surface cleaning is performed, as recommended. This additional specificity may be required for applications on concrete. The specific method is at the direction of the material provider.
- To improve bicycle ride quality, allow skip line markings in the key-hole lane to use 0.090-inch or 90 mils-thick preformed thermoplastic material.

- Divide the “Two Reactive Component Pavement Marking System” material into two material types: “Two Reactive Component System” and “Two Reactive Component Durable Paint System.” The application method of the first would remain unchanged. The durable paint system, however, would be limited to lower conflict areas. It will only be spray applied, each coat in multi-coat applications must completely dry, and drying cannot be accelerated by applying heat.

Dev Section 976—Green-Colored Pavement Marking Materials

- Clarify that products must meet the Part A laboratory requirements in FM 5-622 to qualify for the APL.
- Divide the “Two Reactive Component Pavement Marking System” material into two material types: “Two Reactive Component System” and “Two Reactive Component Durable Paint System.”
- Add a section for “Material Type” under “Composition,” in which the material requirements are detailed. Preformed thermoplastic should conform to the physical requirements of 971-6, Table 971-12. The two reactive component system should have a high solids content of 80 to 100 percent. The durable paint system is a modified waterborne paint that includes two reactive components.
- The durable paint system must pass a curl test to determine shrinkage potential. The test and criterion have not been fully developed.
- Add that the material must meet color requirements (i.e., luminance and chromaticity) both before and after polishing and accelerated weathering.

FM 5-622—Florida Test Method for Evaluation of Pavement Markings Materials with Friction Requirements

- Add an accelerated weathering test to pre-qualification (Part A). Provide default exposure settings detailed in the report (Table 4-7) and an exposure time of 240 hours (10 days).
- Clarify that one extra panel for friction and weathering will be kept for referee testing.

Guidelines

The guidelines, titled *Green-Colored Pavement Markings for Florida Bicycle Facilities*, were written for a broad audience, including FDOT designers, engineers, inspectors, private contractors, and academia. The guidelines provide background on the benefits of GCPMs, examples of bicycle facilities that may warrant GCPMs, material types and test requirements, application methods, and performance issues. The guidelines mirror the proposed specifications and incorporate other best practices.

Further Research

The team recommends further research on the following topics:

- Development of a curl test to measure the shrinkage potential of liquid coatings.
- Evaluate a water absorption test for durable paint materials (Kampasakali et al., 2011).
- Comparison of previous generation (System A) and next generation (System B) epoxy-modified acrylic paints.
- Cost-effectiveness of each GCPM material type for different levels of traffic conflict.
- Cost-effectiveness of manually applied GCPM versus automated application systems.
- Colorfastness of different formulations of epoxy systems.
- Wear resistance of other MMA products.

Implementation Plan

Audience

The primary audience for this project is the FDOT State Materials Office, State Safety Office, Office of Design, district-level engineers, and inspectors. In addition, GCPM material suppliers and installers are also essential to research product audiences.

Impediments to Implementation

- The first impediment to implementation is inadequate dissemination of information to end users. Therefore, the implementation plan should include activities to help convey the results.
- The recommended material specifications could exclude certain material types and, consequently, some vendors. This could cause conflict between the DOT and private entities.
- Lack of adequate training could delay or otherwise complicate implementation.
- Product approval will also increase testing costs due to accelerated weathering.

Activities for Implementation

Some key activities for implementation include the following:

- Identify leadership groups and individuals.
- Finalize the implementation products (i.e., specifications, test methods, and guideline document). The test method for shrinkage potential requires additional development.
- Deliver implementation products to end users.

- Conduct workshops with end users through district visits or webinars.
- Discuss the topics in conferences.
- Follow up with leadership on a regular basis to discuss the effectiveness of implementation.

Criteria for Judging Progress and Consequences of Implementation

The following are key criteria for judging the progress and consequences of implementation plans:

- The service life of new GCPM installations.
- The number of GCPM installations within each district and municipality may reflect progress.
- The number of presentations at technical working group meetings, safety conferences, bicycle association meetings, etc.

The consequences of implementation are improved service life of GCPM installations.

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APPENDIX A
FIELD SURVEY DETAILS

An overview of the site location, general observations, and notable distresses are presented. The sites are grouped based on the material type, and underneath the groups, the sites are arranged in the order they were surveyed.

Thermoplastic Sections

Site 15

- Construction and Materials
    - The bike lane was constructed in October 2018 on a new DGFC substrate built in the same period (Figure A-1). The bike lane is in District 4, Indian River County.
- Observation
    - Overall good condition.
    - Minor overheating issues (construction problem).
    - Hairline cracks around edges of some skips.
    - One localized delamination on one of the skips.

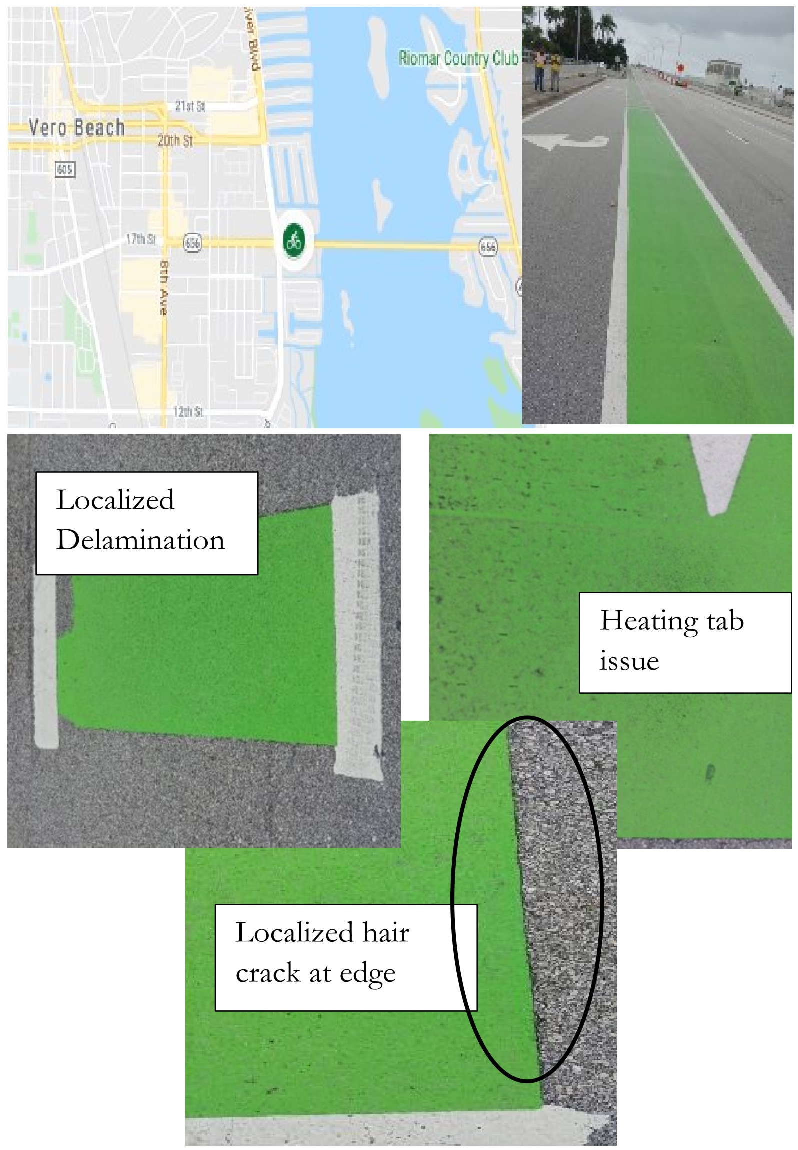

Figure A-1. Site 15-Location and Distresses.

Site 8

- Construction and Materials
  - The bike lane was constructed in October 2018 on a concrete bridge and extended to a DGFC substrate built-in February 2013 (Figure A-2). The bike lane is in District 4, Indian Martin County.
- Observation
  - Overall good condition.
  - Minor overheating issues (construction problem).
  - Dark color under trees.
  - One localized longitudinal crack; lab investigation on cores indicates the crack is structural related and extends about 5 inches deep.

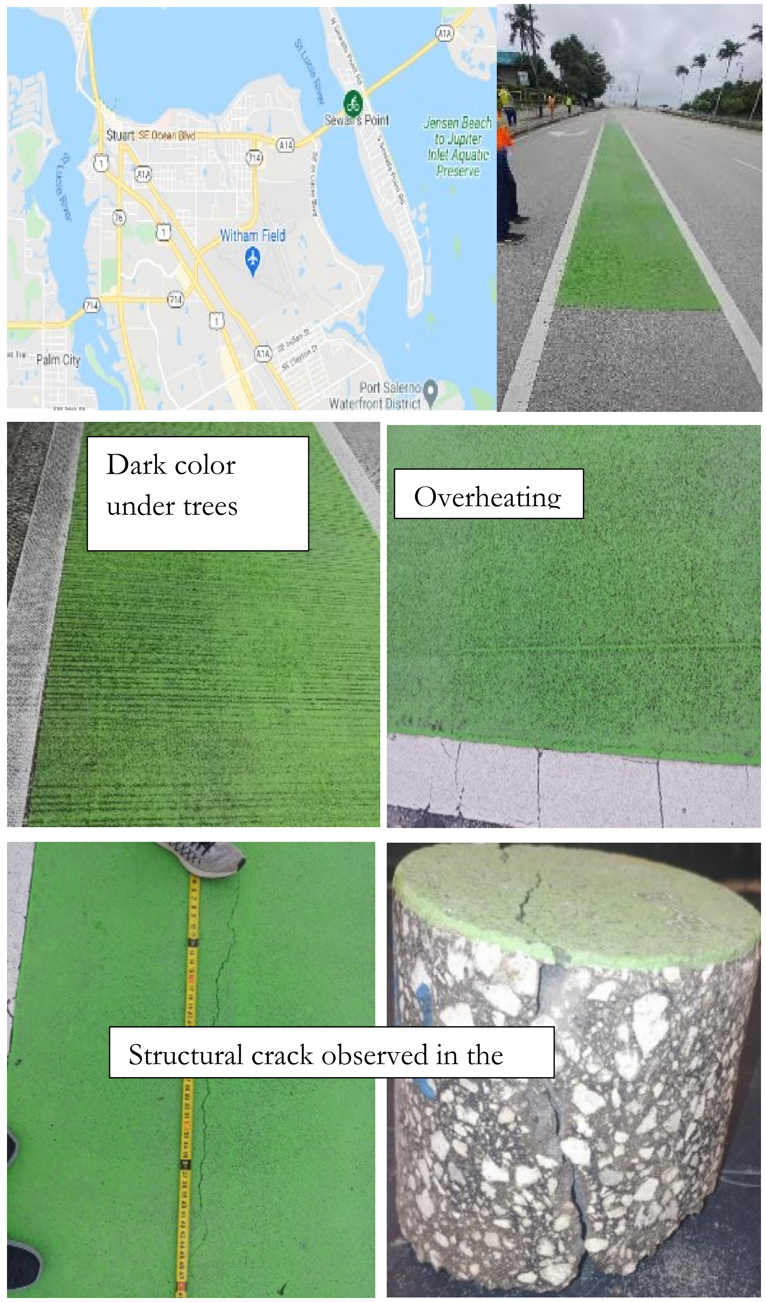

Figure A-2. Site 8-Location and Distresses.

Site 10–13

- Construction and Materials
  - The bike lane was constructed in October 2018 on a DGFC substrate built-in April 2013 (Figure A-3). The bike lane is in District 4, Indian Martin County.

- Observation
  - The research team observed minor overheating issues (construction problem).
  - Hair cracks around edges.
  - The varying texture from one place to another. May be due to different treatment.
  - In general, the lane is in good condition.

Figure A-3. Site 10 through 13-Location and Distresses.

Site 26

- Construction and Materials
    - This thermoplastic bike lane was constructed in March 2019 on a dense-graded substrate built on the same day (Figure A-4). the bike lane is in District 4, Palm Beach County.

- Observation
    - Overall good condition.
    - Small delamination. It looks like a dent from a sharp object.

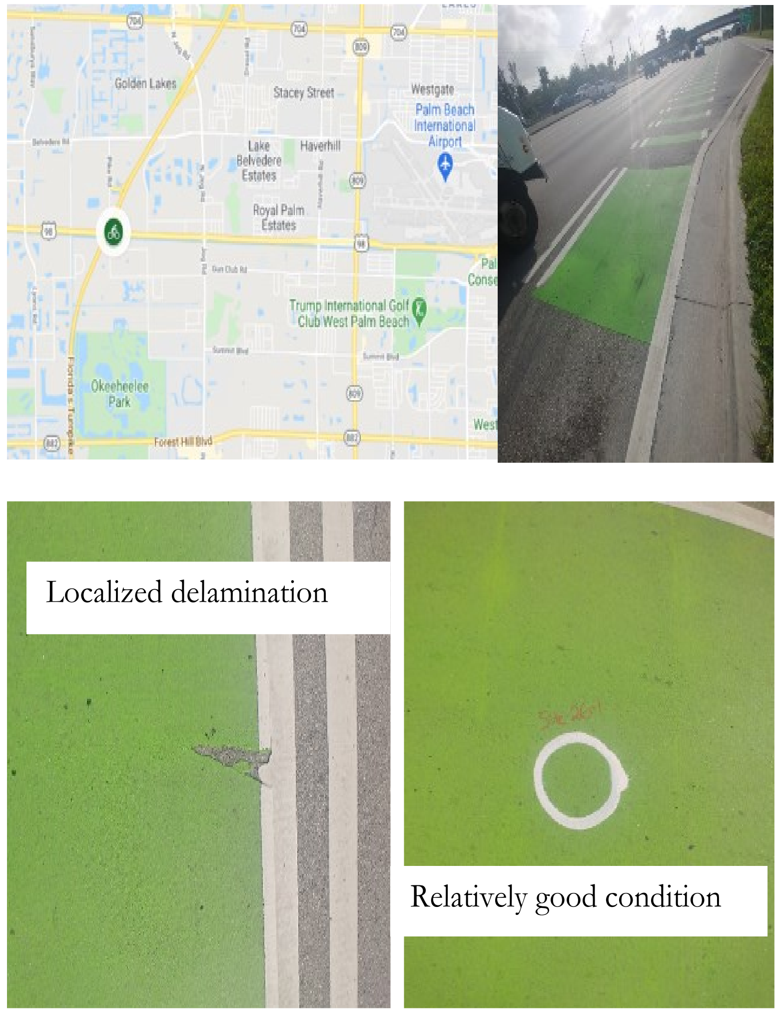

Figure A-4. Site 26-Location and Distresses.

Site 22

- Construction and Materials
  - This thermoplastic bike was lane constructed in December 2019 on a DGFC substrate. The age of the substrate is unknown (Figure A-5). The Bike lane is in District 4, Broward County.

- Observation
  - Overall poor condition.
  - Severe Delamination.
  - Delamination reduced the green bike lane treatment to less than 60 percent.
  - Thermoplastic could easily peel off.

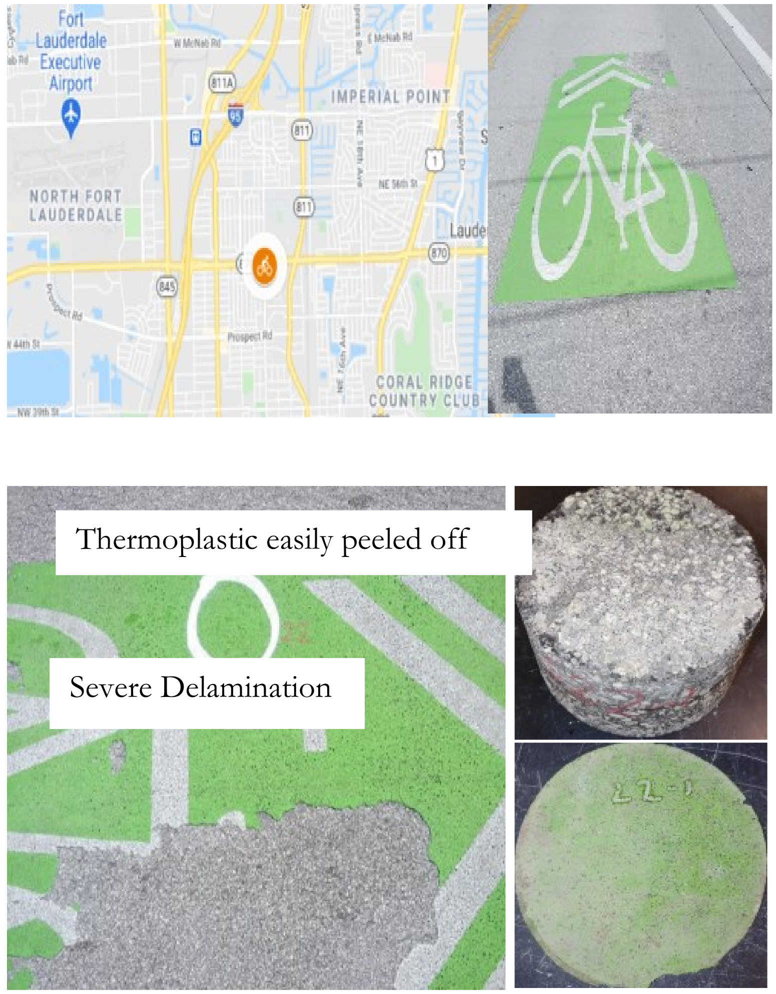

Figure A-5. Site 22-Location and Distresses.

Site 24

- Construction and Materials
  - This site was constructed in June 2017 on a DGFC substrate. The thermoplastic was applied to the pavement immediately after construction (Figure A-6). The Bike lane is in District 4, Broward County.

- Observation
  - Overall poor condition.
  - Skid marks, especially on turning.
  - GCPM on the shoulder was severely delaminated.
  - Thermoplastic is worn out and very dirty near gutters.
  - Heat tab issues and splitting along seams.
  - Cracks were observed at the edges of the boxes.

Figure A-6. Site 24-Location and Distresses.

Site 28 and 29

- Construction and Materials
  - Site 28 and 29 fall in the same lane, split into two parts, 28 and 29, before and after exit (Figure A-7) The site was constructed in 2015 on a DGFC substrate. The substrate was built during the same period. The bike lane is in District 6, Dade County.

- Observation
  - Overall poor condition.
  - Severe delamination was observed on both sites 28 and 29.
  - Many heat tabs issues, probably due to poor construction.

Figure A-7. Site 28 and 29-Location and Distresses.

Site 1

- Construction and Materials
  - By the time of the survey, the thermoplastic and its substrate (OGFC) clocked 3.25 years. They were both built in June 2017. Traffic entering and exiting I75 crosses the green bike lane. The lane is on SR43/US301, in district 1, Manatee County. Figure A-8 shows observed distresses.

- Observation
  - Overall, the thermoplastic treatment is in poor condition.
  - Seams are splitting, both in trafficked and un-trafficked locations.
  - Cracks were observed within sheets, both in trafficked and un-trafficked locations.
  - Thermal compatibility may be a factor. But fatigue from traffic load could be another reason.
  - Sections conflicting with traffic are dull.

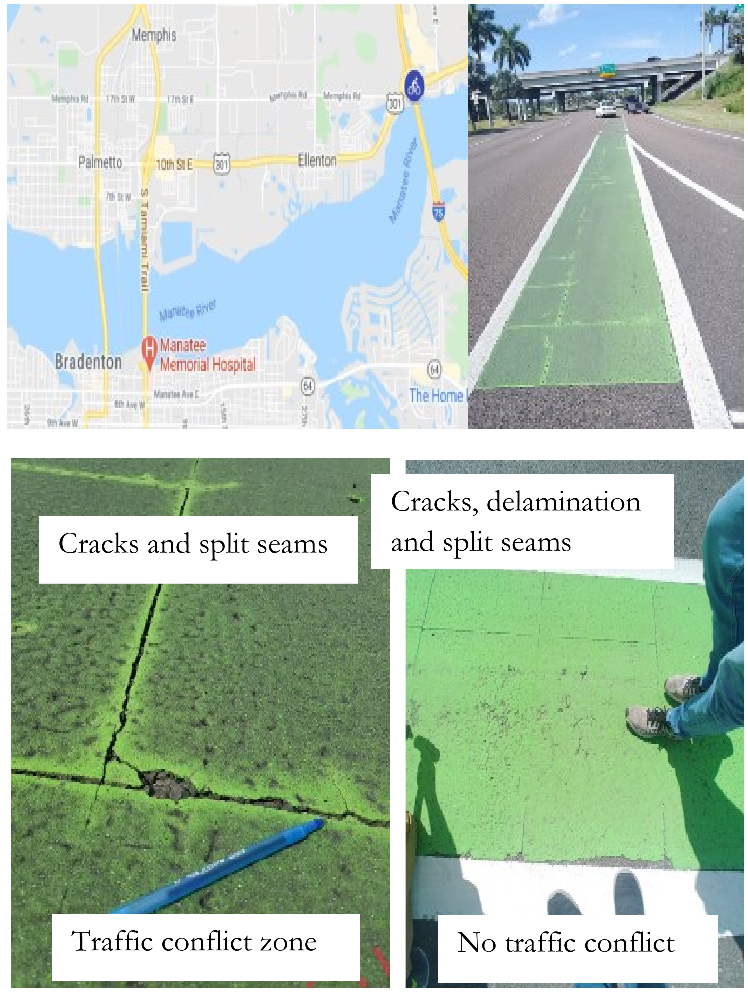

Figure A-8. Site 1-Location and Distresses.

Site 3

- Construction and Materials
    - By the time the field survey was conducted, the thermoplastic and its substrate (DGFC) were three years old. They were both built in October 2017. The lane is on SR699 (Gulf Blvd/106th Ave.) in District 7, Pinellas County.

- Observation
    - Overall the thermoplastic treatment is in relatively good condition.
    - The survey found limited delamination and cracks in areas of poor drainage (Figure A-9).

Figure A-9. Site 3-Location and Distresses.

Site 4

- Construction and Materials
  - By the time the field survey was conducted, the thermoplastic and its substrate (DGFC) were three years old. They were both built in October 2017. The lane is on SR699 (Gulf Blvd/CR694), in District 7, Pinellas County.
- Observation
  - Overall the thermoplastic treatment is in relatively good condition.
  - Localized cracks and delamination were observed (Figure A-10).
  - Microcracks within boxes.
  - A sealer was used, as was seen on the underside of the delamination (Figure A-10).

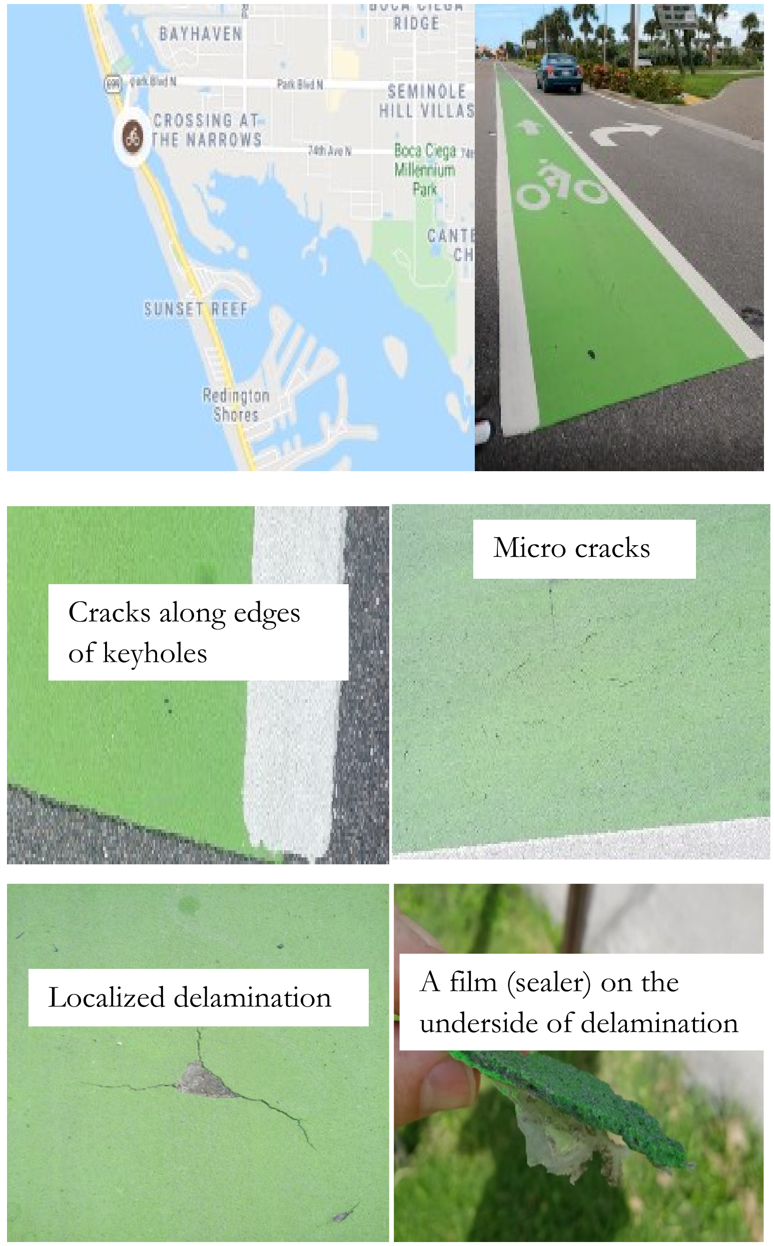

Figure A-10. Site 4-Location and Distresses.

Site 5

- Construction and Materials
  - By the time the field survey was conducted, the thermoplastic and its substrate (DGFC) were three years old. They were both built in October 2017. The lane is on SR699 (Walsingham Rd/Gulf Blvd), in District 7, Pinellas County.

- Observation
  - Overall good condition.
  - Moderate cracks are probably related to traffic and thermal (Figure A-11). It may also be structural/asphalt related.
  - Slight wearing.

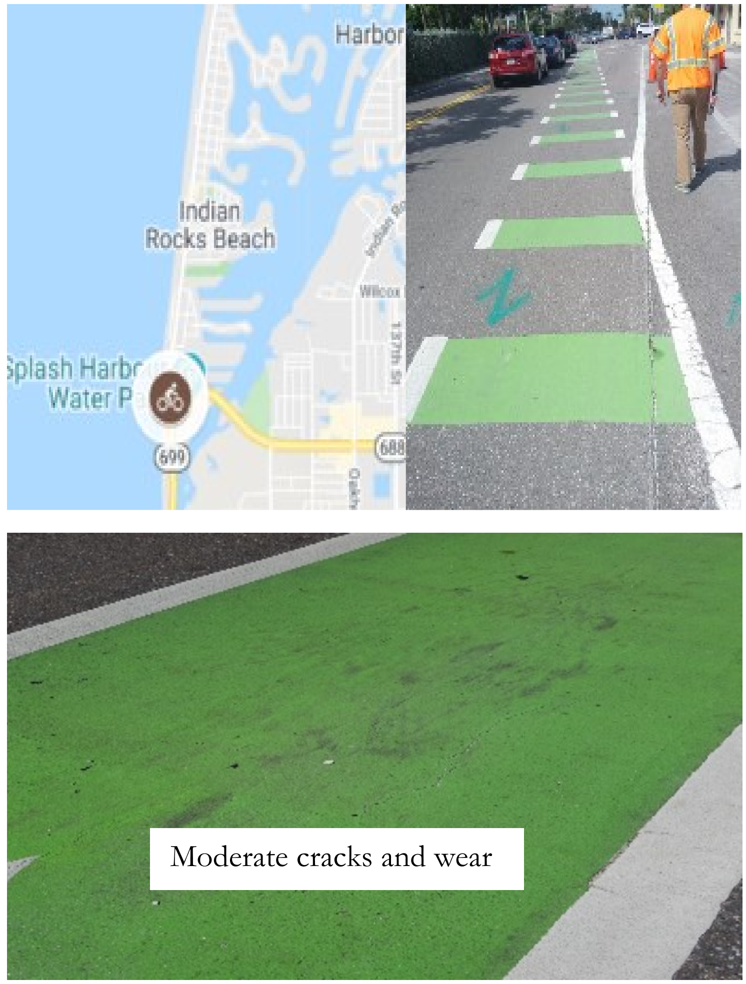

Figure A-11. Site 5-Location and Distresses.

Site 2

- Construction and Materials
    - By the time the field survey was conducted, the thermoplastic and its substrate (DGFC) were two years old. They were both built in September 2018. The lane is on SR60, in District 7, Hillsborough County.

- Observation
    - Overall good condition (Figure A-12).
    - It's a lengthy application in a busy downtown.

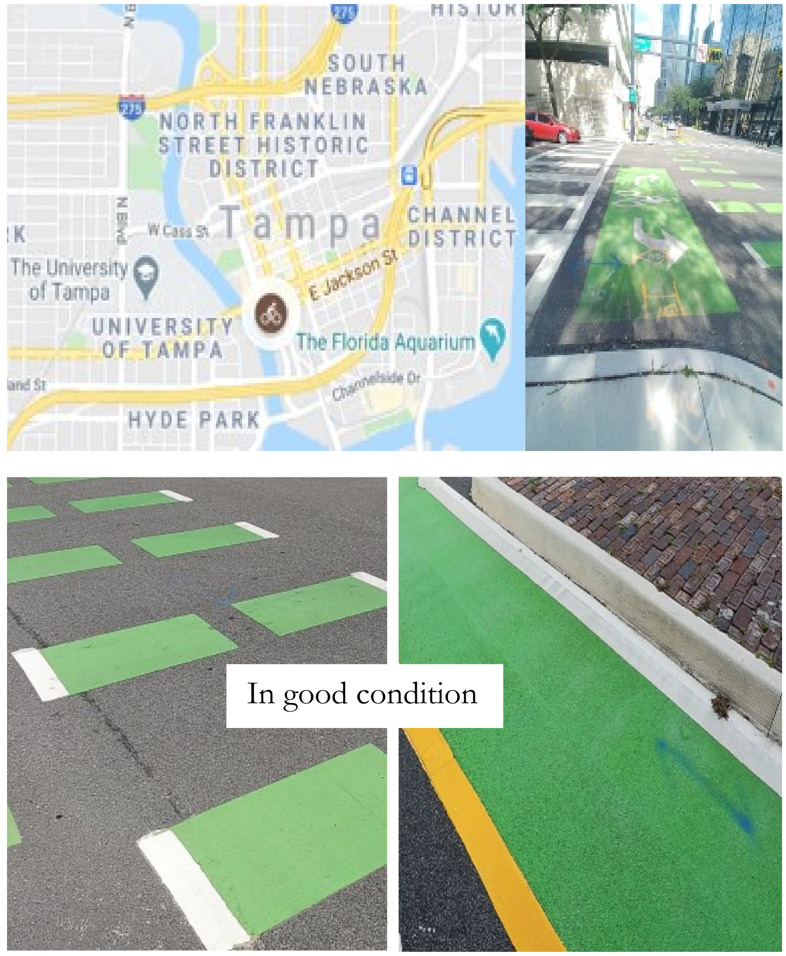

Figure A-12. Site 2-Location and Distresses.

Epoxy-Modified Acrylic Sections

Site 7

- Construction and Materials
  - The epoxy-acrylic treated lane and its substrate (DGFC) were three years old during the survey. Both were built in October 2017. The bike lane is on SR 615 from St. Lucie Blvd to SR-5, in district 4, St. Lucie County.
- Observation
  - The northbound (NB) bike lane, located adjacent to the gutters, was in poor condition.
  - The southbound (SB) lane, constructed off-gutters, is in relatively good condition.
  - Significant cracking on shoulder lanes (Figure A-13).
  - Epoxy-acrylic peeling off with HMA.
  - Skips edges badly cracked.
  - Longitudinal cracks were observed at the center turning box lane.
  - Since the damages are mainly on the gutter's proximity, less compacted substrates and perhaps water infiltration could be the primary sources of the problems.

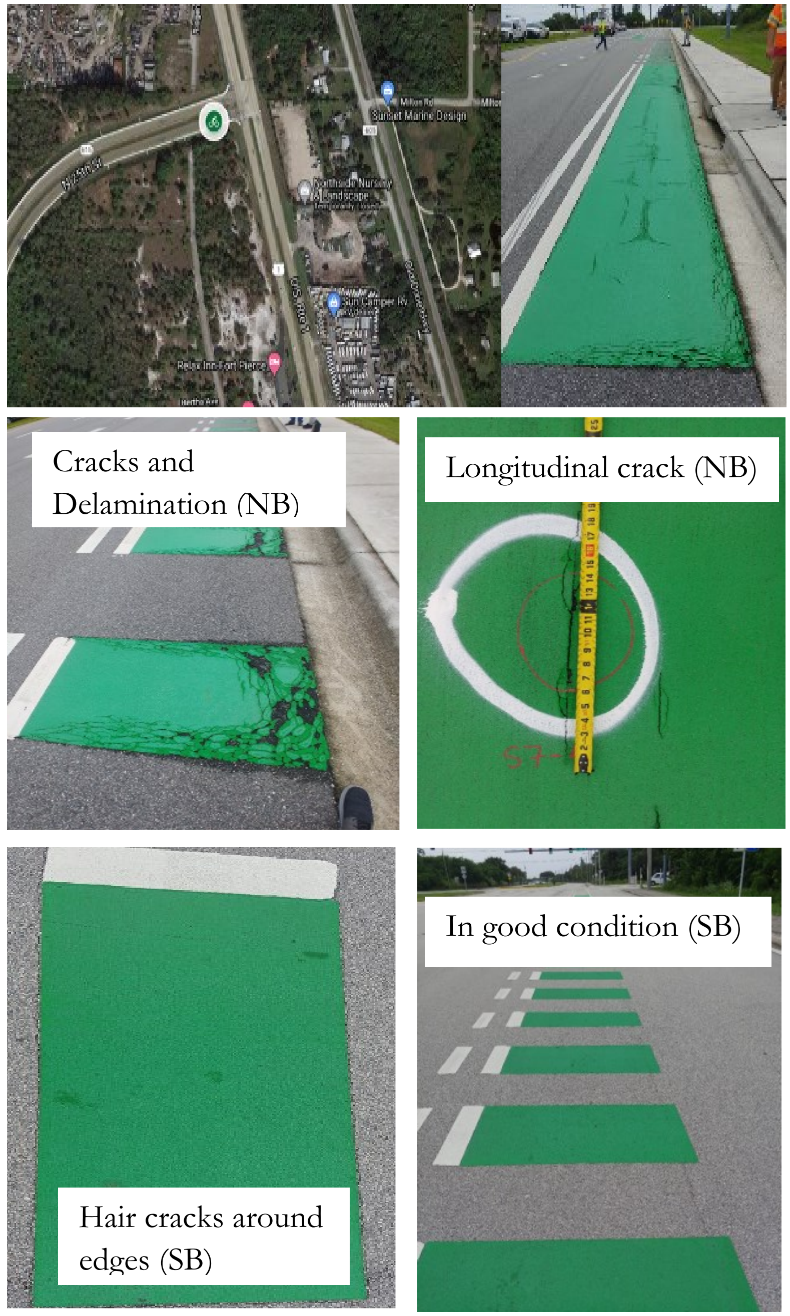

Figure A-13. Site 7-Location and Distresses.

Site 16

- Construction and Materials
    - This epoxy-acrylic treated lane and its substrate (DGFC) were 1.5 years old during the survey. Both were built in April 2019. The bike lane is on US1 and SE Gran Park Way, in District 4, Martin.

- Observation
    - Good condition (Figure A-14).
    - The survey observed a few hairline cracks around the edges of skips.

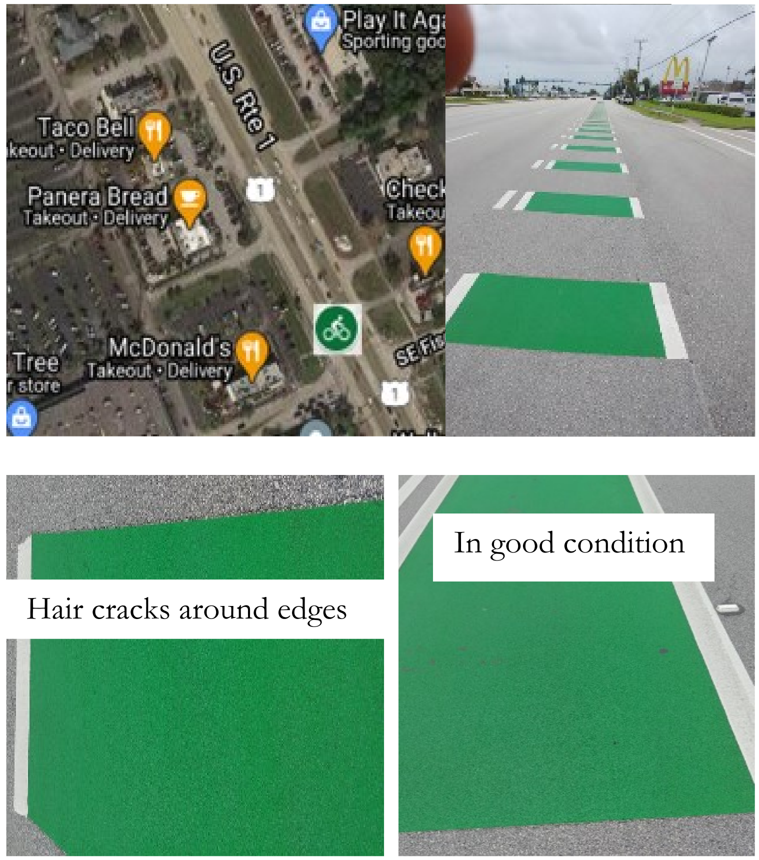

Figure A-14. Site 16-Location and Distresses.

Site 17

- Construction and Materials
  - This epoxy-acrylic treated lane on a DGFC substrate was two years old during the survey. The Epoxy-acrylic treated surface was built in November 2018. Meanwhile, the substrate was estimated to be slightly older. The lane is on 15th St from Australian Ave to Dixie Hwy, in District 4, Palm Beach.
- Observation
  - West of the railroad—poor condition. East of the railroad—fair condition (Figure A-15).
  - The epoxy-acrylic treatment is badly cracked and delaminated with chunks of HMA. The distresses are more pronounced in the westbound direction.
  - The epoxy-acrylic treatment has badly worn out at the intersection .
  - Areas, under trees and along the gutters, are darkened. Some areas seemed to have been underwater.

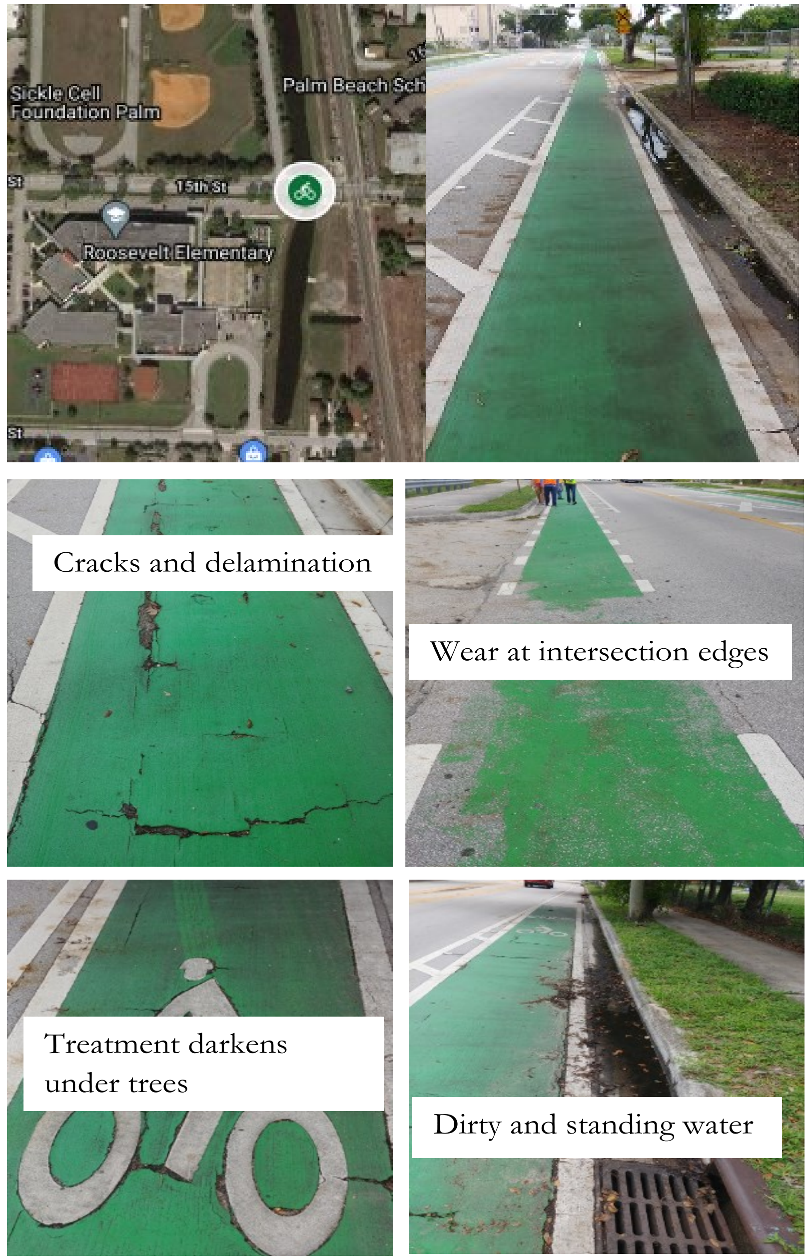

Figure A-15. Site 17-Location and Distresses.

Site 18

- Construction and Materials
  - Site 18 is an Epoxy-acrylic treated bike lane laid on OGFC substrate and extends into a concrete bridge substrate. By the time this field survey was conducted, the Epoxy-acrylic-treated lane was two years old (built in August 2018). Meanwhile, the age of the substrate is not known. The green bike lane is on EB Okeechobee Blvd at I-95, in District 4, Palm Beach.

- Observation (Figure A-16)
  - Poor condition on OGFC substrate.
  - Good condition on concrete substrate.
  - On the OGFC substrate, the epoxy-acrylic is worn out. More Epoxy-acrylic application could be needed for the OGFC substrate.
  - Skips on OGFC substrate were cracked and delaminated.

Figure A-16. Site 18-Location and Distresses.

Site 34

- Construction and Materials
  - The substrate (DGFC) and the epoxy-acrylic treatment were relatively new during the survey period. The green bike lane is on SR80 at Royal Palm Beach Blvd, in District 4, Palm Beach.

- Observation
  - Overall in good condition.
  - Some cracks around the edges of the epoxy-acrylic treatment (Figure A-17).
  - Slight application nonuniformity. Maybe skid mark.

Figure A-17. Site 34-Location and Distresses.

Site 19

- Construction and Materials
  - This is an Epoxy-acrylic treated bike lane laid on a DGFC substrate in May 2017. The substrate and the epoxy-acrylic treatment were constructed at the same period. When the survey was conducted, the treated lane was about 3.25 years old. The green bike lane is on NE 2nd Ave from NE 4th St to George Bush Blvd, in District 4, Palm Beach.

- Observation (Figure A-18)
  - Overall, in good condition.
  - Excessive edge on a few keyholes
  - Localized delamination; could be a construction issue.
  - Color fading in some locations.

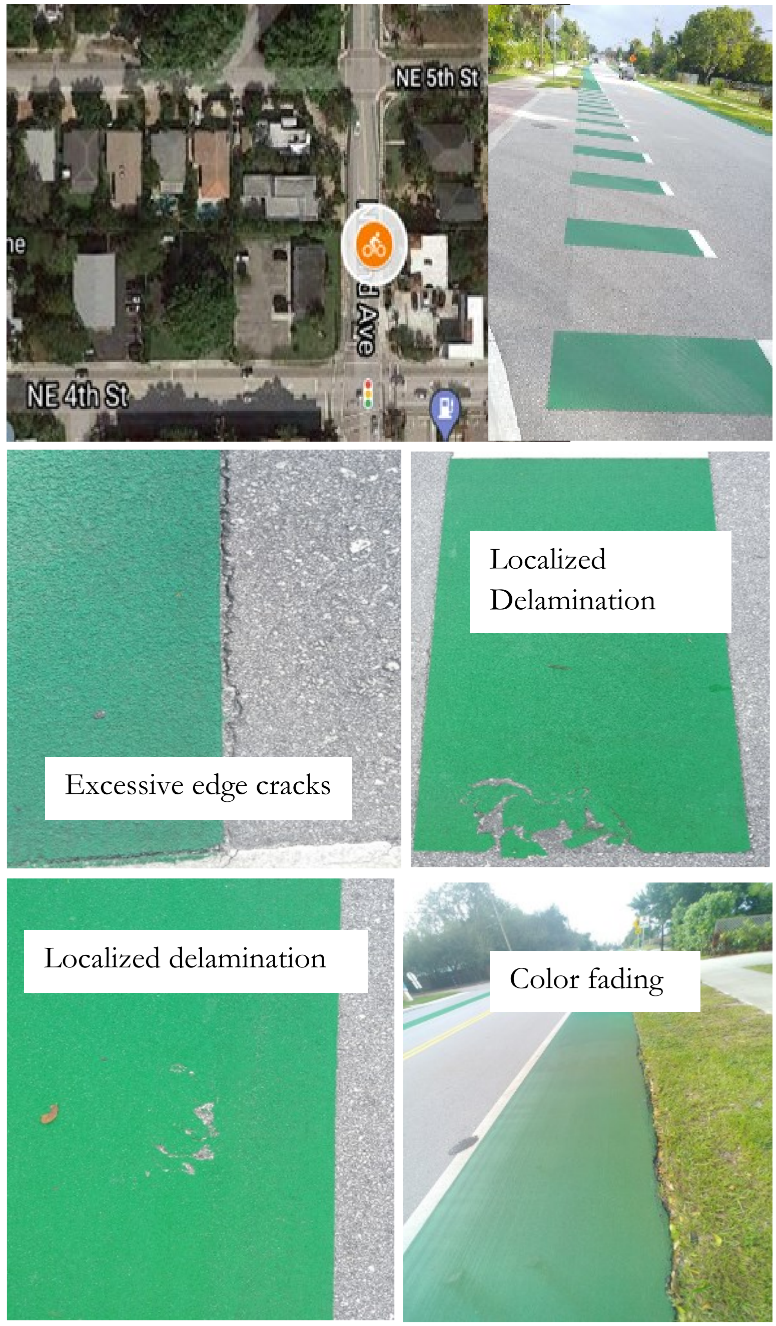

Figure A-18. Site 19-Location and Distresses.

Site 20

- Construction and Materials
  - This is an Epoxy-acrylic treated bike lane laid on an OGFC substrate in February 2018. The substrate and the epoxy-acrylic treatment were constructed at the same period. The treated lane was about 2.5 years old. The green bike lane is on SR 7 from Clint Moore Rd to Atlantic Ave, in District 4, Palm Beach.
- Observation (Figure A-19)
  - Color fades into OGFC.
  - Significant wear near WAWA gas station (NB). It seems the NB application was by spraying, whereby the SB application was by the squeegee.
  - Significant cracking. Maybe due to differential movements.
  - The NB was sprayed, and SB was squeegeed. Lab investigation showed voids filled with epoxy-acrylic for squeegeed sections and open pores for sprayed areas.
  - The spray application does not cover the OGFC aggregates uniformly. On the other hand, squeegee takes a lot of materials to fill in voids.

Figure A-19. Site 20-Location and Distresses.

Site 21

- Construction and Materials
    - This is an Epoxy-acrylic treated bike lane laid on DGFC substrate in November 2016. The substrate is about two years older than the Epoxy-acrylic treatment. When the survey was conducted, the epoxy-acrylic treatment was about four years old. The green bike lane is on N. Ocean Dr. from NE 2nd St to Ne 2nd St. (Road Bends), in District 4, Broward County.

- Observation (Figure A-20)
    - In general, the lane is in relatively good condition.
    - The team observed wear around the corner due to traffic encroaching.
    - Wear in front of a valet parking.
    - A few localized cracks and delamination.

Figure A 20. Site 21-Location and Distresses

Site 23 and 55

- Construction and Materials
  - These are 2.5 years old, two epoxy-acrylic-treated sites separated by a roundabout. The lanes were constructed at the same time in April 2018 on a DGFC substrate. The substrate is slightly older than the epoxy-acrylic treatment. The green bike lanes are on NE 13th St. to Middle River (site 23) and Dixie Hwy from NE 17th CT to Middle River Bridge (site 55), in District 4, Broward County.
- Observation (Figure A-21)
  - Overall poor condition.
  - Excessive cracking and delamination.
  - Constructed adjacent to the gutter. Water could be one of the destruction factors. Another factor could be thermal cracking and low-density substrate.
  - The adjacent crosswalk was intact though it was made of epoxy-acrylic as well. The observed difference was the construction pattern.
  - Most problems were observed on site 55 on dixie highway.

Figure A-21. Site 23 and 55-Location and Distresses.

Site 56

- Construction and Materials
    - This is 205 years old epoxy-acrylic treated green bike constructed in April 2018 on a DGFC substrate. The lane was built at the same time as sites 23 and 55. However, it is in excellent condition compared to the other two lanes. The green bike lane is on NE 13th Street from NE 4th Ave to NE 9th Ave, in District 4, Broward County.

- Observation (Figure A-22)
    - The survey observed a few localized cracks.
    - Wear and dirt under tree shades and roadside parking.
    - The lanes are in good condition.

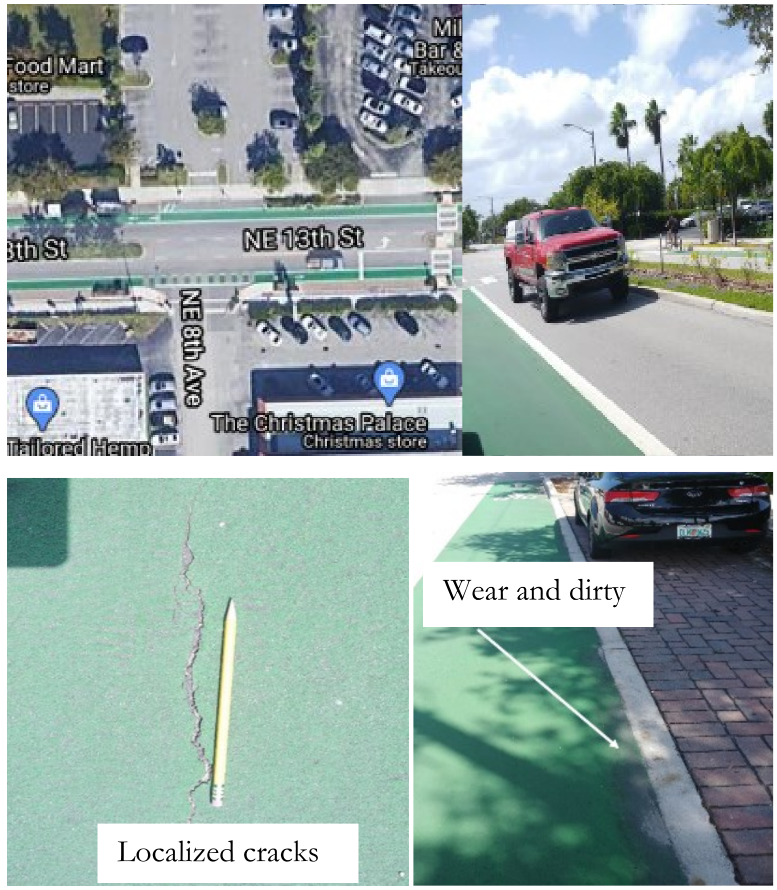

Figure A-22. Site 56-Location and Distresses.

[Site 59]

- Construction and Materials
  - This is an Epoxy-acrylic treated bike lane constructed around mid-2018 on a DGFC substrate. By the time the survey was conducted, it was two years old. The age of the substrate is not known, but one can estimate its age to be like a year or two older than the epoxy-acrylic treatment. The green bike lane is on SR 968(SW 1st St) from SW 2nd Ave. to US-1 (Biscayne Blvd), in District 6, Dade County.
- Observation (Figure A-23)
  - In general, based on the above observation, the bike lane is mostly in good condition.
  - The research team observed vehicle skid marks and a bit of color fading (due to traffic?). The lane is in the city center with a couple of roadside parking alongside. Therefore, traffic conflicting the bike lanes is inevitable.
  - Cracks at edges of some keyhole.
  - Delamination and cracking at sections corresponding to heavy traffic conflicts.

Figure A-23. Site 59-Location and Distresses.

Site 30

- Construction and Materials
  - This is an Epoxy-acrylic treated bike lane constructed on a DGFC substrate. The epoxy-acrylic treatment and its substrates are five years old. The green bike lane is on Rickenbacker Causeway in district 6, Dade County.

- Observation (Figure A-24)
  - Rougher and relatively thicker surface treatment on the bike lane than most of the sites surveyed.
  - The bike lane is in the city center with a couple of roadside parking alongside. Therefore, traffic conflicting the bike lanes is inevitable.
  - Cracks at edges of some keyholes.
  - Color fades.
  - Except for color fading, the lane is in good condition.

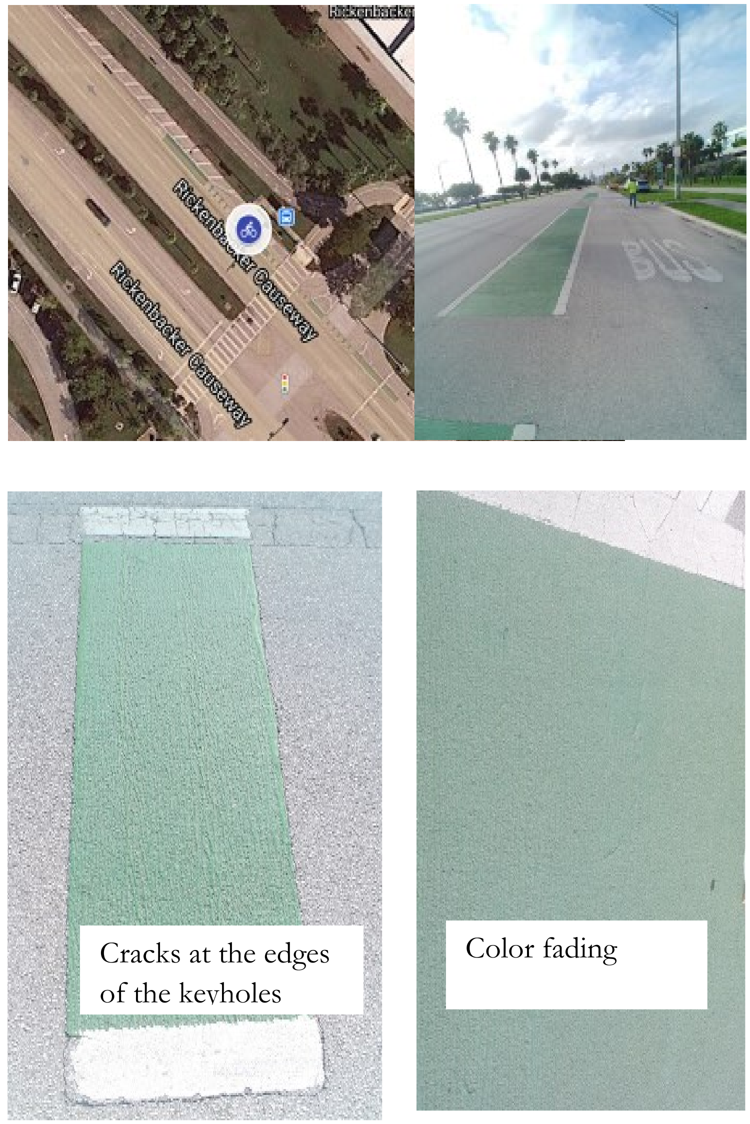

Figure A-24. Site 30-Location and Distresses.

Epoxy Section

Site 35

- Construction and Materials
  - This is an Epoxy-glass-mixed treated bike lane laid on a DGFC substrate in January 2017. The substrate and the epoxy treatment were constructed at the same period. When the survey was conducted, the treated lane was about 3.5 years old. The green bike lane is on NE 2nd Ave from NE 4th St to George Bush Blvd, in District 4, Palm Beach.
- Observation (Figure A-25)
  - Overall condition is fair.
  - Raveling throughout the bike lane. Maybe due to glass popping out of the mix/treatment.
  - Nonuniform color, in some places very dull.
  - Some areas have cracks, but these cracks are structural/asphalt.

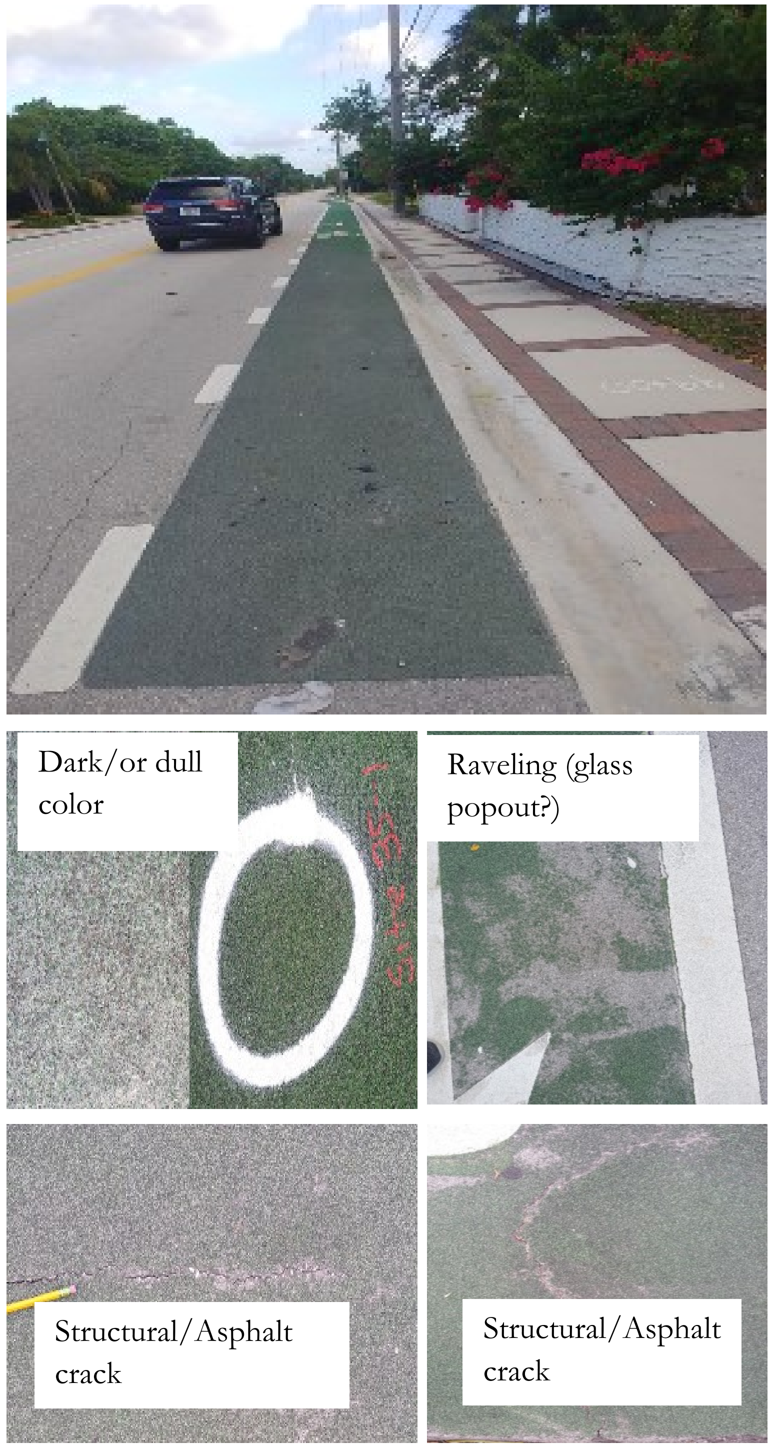

Figure A-25. Site 35-Location and Distresses.

MMA Sections

Site 58/27

- Construction and Materials
  - These sites are MMA treated bike lanes covering N. Rosalind and N. Magnolia streets in District 5, Orange County. The age of the MMA and a DGFC substrate are currently not known to the researchers.

- Observation (Figure A-26)
  - The MMA is completely worn out from traffic exposure.
  - We observed structural/Asphalt related cracks.
  - In general, the MMA treated lanes are in poor condition.

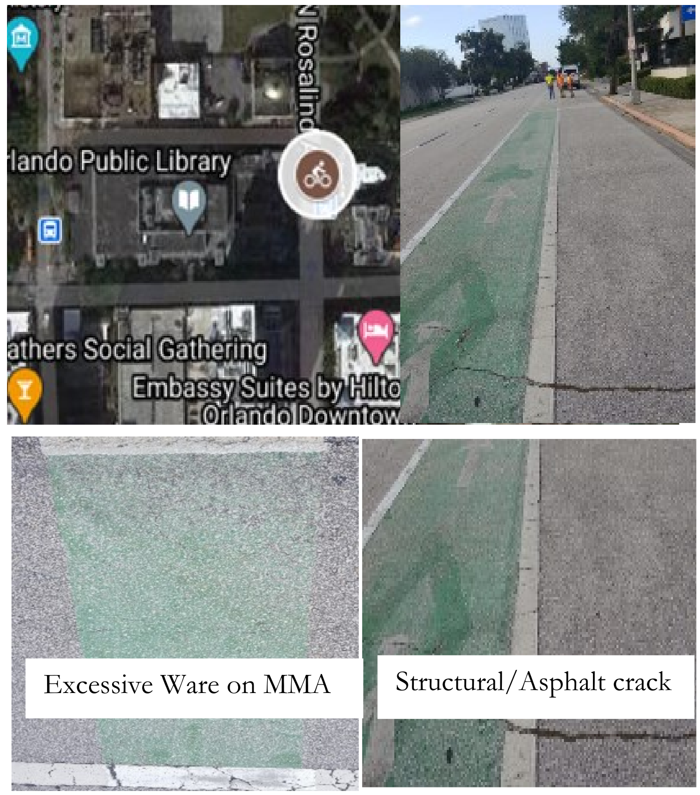

Figure A-26. Site 58 and 27-Location and Distresses.

Site 57

- Construction and Materials
  - As is for sites 27 and 58, this bike lane is also treated with MMA product. The bike lane is on E Livingston Street from I-4 to Magnolia Ave, in District 5, Orange County. The age of the MMA and a DGFC substrate are currently not known to the researchers.

- Observation (Figure A-27)
  - Wearing on the MMA.
  - Structural cracks.
  - Fading color and dirty next to gutters.
  - The rate of deterioration (wearing and cracks) is less than the MMA observed on sites 58 and 27. It looked like the MMA on-site 57 was reapplied.
  - In general, the site is in poor condition.

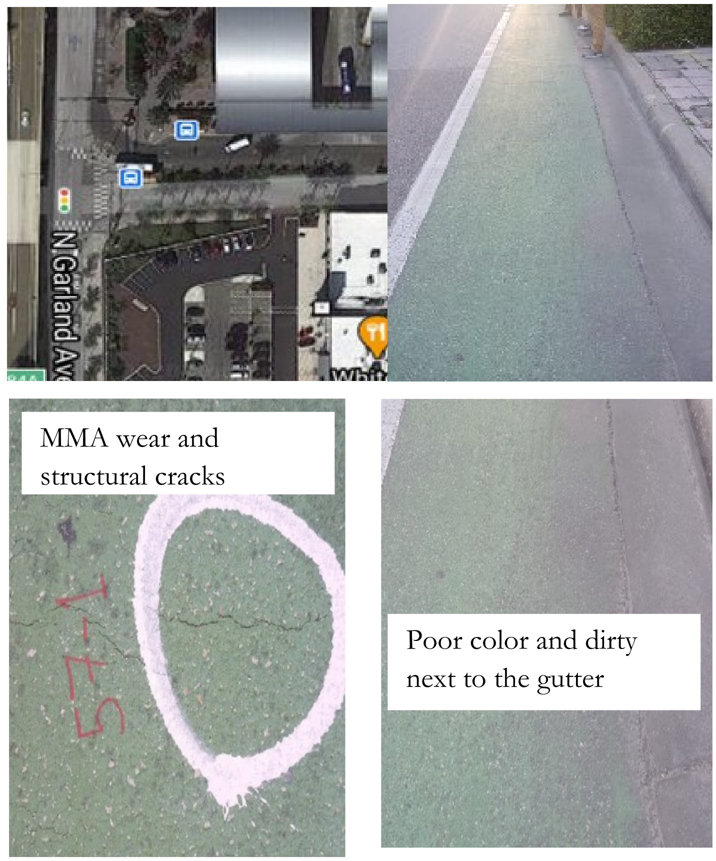

Figure A-27. Site 57-Location and Distresses.

APPENDIX B

PULL-OFF TEST RESULTS

Table B-1. Pull-Off Test Results.

Specimen ID (Material)	Test point	Peak load (PSI)	Failure Location
1-1 (Thermoplastic)	1	68.5	Top HMA layer
	2	65.7	Top HMA layer
	3	60.3	Top HMA layer
	Average	**64.8**	-
Site 21-1 (Epoxy-Acrylic)	1	137.5	HMA/HMA bond
	2	132.7	HMA/HMA bond
	3	118.2	HMA/HMA bond
	Average	**129.5**	-
Site 23-3 (Epoxy-Acrylic)	1	145	Epoxy pilled off
	2	160.2	Epoxy pilled off
	3	162	Epoxy pilled off
	Average	**155.7**	-
Site 5-1 (Thermoplastic)	1	256.1	HMA/HMA bond
	2	260.5	Into the Substrate
	3	242.6	Into the Substrate
	Average	**253.1**	-
Site 2-1 (Thermoplastic)	1	263	HMA/HMA bond
	2	240.3	HMA/HMA bond
	3	267.6	Into the substrate (top layer)
	Average	**257.0**	-
Site 4 (Thermoplastic)	1	sitting load	Just below the thermoplastic
	2	sitting load	Just below the thermoplastic
	3	47.1	Top HMA layer (poor aggregates?)
	Average	**47.1**	Already failed?
Site 15C1 (Thermoplastic)	1	93.1	HMA/HMA bond
	2	134.8	HMA/HMA bond
	3	125.4	HMA/HMA bond
	Average	**117.8**	-
Site 34-1 (Epoxy-Acrylic)	1	136.3	HMA/HMA bond
	2	62.6	HMA/HMA bond (partially debonded before the test?)
	3	140.1	HMA/HMA bond
	Average	**113.0**	-
Site 17-3 (Epoxy-Acrylic)	1	167.1	Near surface
	2	164.8	Near-surface
	3	141	Near-surface into GCPM Materials
	Average	**157.6**	-

Table B-1. Pull-Off Test Results (Continued).

Specimen ID	Test point	Peak load (PSI)	Failure Location
Site 28-1 (Thermoplastic)	1	83.6	HMA/HMA bond
	2	80.2	HMA/HMA bond
	3	98.3	HMA/HMA bond
	Average	**87.4**	-
Site 20-2 (Epoxy-Acrylic)	1	63.6	OGCFC/DG HMA bond
	2	57.5	OGCFC/DG HMA bond
	3	63.1	OGCFC/DG HMA bond
	Average	**61.4**	-
Site 20-3 (Epoxy-Acrylic)	1	1.91	OGCFC/DG HMA bond
	2	2.87	OGCFC/DG HMA bond
	3	3.82	OGCFC/DG HMA bond
	Average	**2.9**	-
Site 20-4 (Epoxy-Acrylic)	1	32.5	OGCFC/DG HMA bond
	2	38.2	OGCFC/DG HMA bond
	3	38.2	OGCFC/DG HMA bond
	Average	**36.3**	-
Site 18-1 (Epoxy-Acrylic)	1	103.3	Into the layer below OGFC
	2	102.3	Into the layer below OGFC
	3	115.2	Into the layer below OGFC
	Average	**106.9**	-
Site 18-2 (Epoxy-Acrylic)	1	49	Into the layer below OGFC
	2	46.5	Into the layer below OGFC
	3	50.3	Into the layer below OGFC
	Average	**48.4**	-
Site 18-3 (Epoxy-Acrylic)	1	90.9	Intermediate HMA layer
	2	52.2	Intermediate HMA layer
	3	39.4	Intermediate HMA layer
	Average	**60.8**	-
Site 7-1 (Epoxy-Acrylic)	1		
	2	1.197	Just under surface
	3	2.396	Just under surface
	Average	**1.8**	-
Site 7-3 (Epoxy-Acrylic)	1	204.3	Into the layer below DGFC
	2	208.2	Into the layer below DGFC
	3	201.3	Into the layer below DGFC
	Average	**204.6**	-
Site 26-1 (Thermoplastic)	1	112.1	Into the layer below DGFC
	2	163.7	Into the layer below DGFC
	3	149.2	Into the layer below DGFC
	Average	**141.7**	-

Pull-Off Test Results Discussion

Site 21 – Core 1: Epoxy Treatment Age: 4 years; DGFC Substrate Age: 6 years

The research team determined that the failure mechanism for this specimen was 100% Substrate (HMA to HMA bond) failure (Figure B-1). However, the strength achieved (129.5 psi) was relatively low (<150 psi). Therefore, an additional surface pull-off test is needed (with a shallow cut). At the current state, the Epoxy to DGFC bond strength is inconclusive.

Figure B-1. Pull-Off Test for Specimen 21-1.

Site 1 – Core 1: Thermoplastic Treatment Age: 3 years; OGCF Substrate Age: 3 years

The research team determined that the failure mechanism for this thermoplastic-treated specimen was 100% substrate failure (Figure B-2). However, the achieved Pull off strength (64.8 psi) was relatively very low (<<150 psi). At this failure mechanism and low strength, deciding on the thermoplastic-to-substrate bond is challenging. Therefore, an additional surface pull-off test on a shallow-cut specimen is needed.

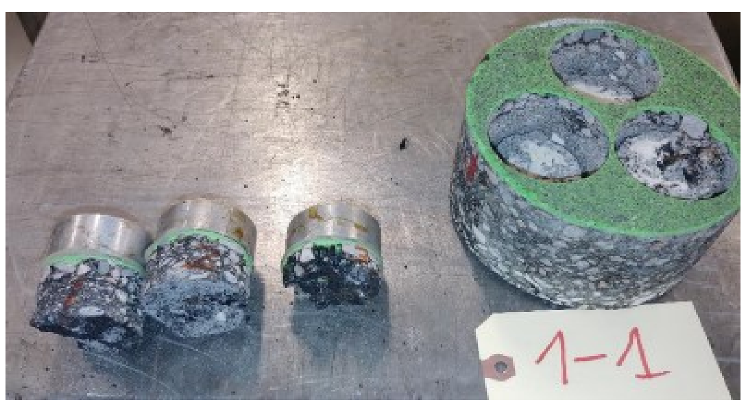

Figure B-2. Pull-Off Test for Specimen 1-1.

Site 23 – Core 3: Epoxy Treatment Age: 2.5 years; DGFC Substrate Age: Slightly older

The research team determined that the failure mechanism for this specimen was a clean delamination/debond of epoxy from the Substrate (Figure B-3). The average pull-off strength was 155.7 psi (>150). The Epoxy treatment meets the minimum bond strength.

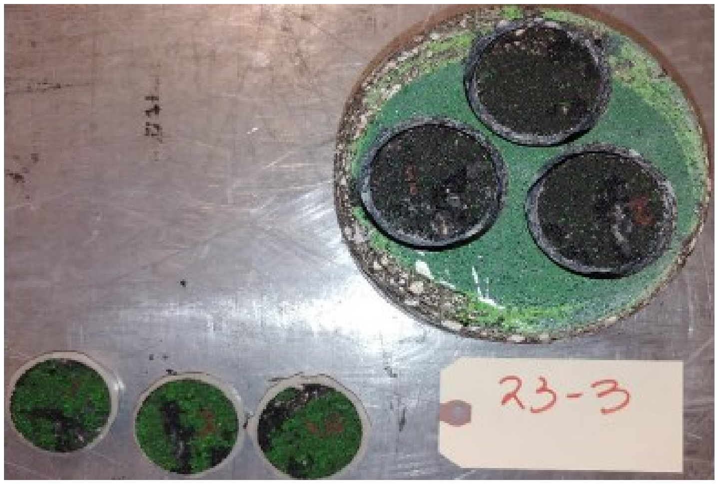

Figure B-3. Pull-Off Test for Specimen 23-3.

Site 5 – Core 1: Thermoplastic Treatment Age: 3 years; DGFC Substrate Age: 3 years

The research team determined that the failure mechanism for this specimen was 100% substrate failure (Figure B-4). The average pull-off strength (253.1 psi) was relatively high (<<150 psi). The thermoplastic bond did not fail, implying that the thermoplastic-substrate bond is strong (>253.1psi).

Figure B-4. Pull-Off Test for Specimen 5-1.

Site 15 – Core C1: Thermoplastic Treatment Age: 2 years; DGFC Substrate Age: 2 years

The research team determined that the failure mechanism for this specimen was 100% substrate failure (HMA to HMA bond) (Figure B-5). However, the strength at failure (117.8 psi) was relatively low (<150 psi). Therefore, an additional surface pull-off test is needed (with a shallow groove). At the current state, the thermoplastic/DGFC bond strength is inconclusive.

Figure B-5. Pull-Off Test for Specimen 15-C1.

Site 34 – Core 1: Epoxy Treatment Age: New; DGFC Substrate Age: New

The research team determined that the failure mechanism for this specimen was 100% substrate failure (HMA to HMA bond). Maybe due to the ingress of water, the bond was already partially de-bonded. The average strength (113 psi) was relatively low (<150 psi) (Figure B-6). The failure mechanism and low strength imply that an additional surface pull-off test is needed (with a shallow cut). At the current state, the thermoplastic to substrate bond strength is inconclusive.

Figure B-6. Pull-Off Test for Specimen 34-1.

Site 17 – Core 3: Epoxy Treatment Age: 2 years; DGFC Substrate Age: Slightly older

This is an Epoxy-treated-DGFC specimen. The research team determined that the failure mechanism for this specimen was 100% near-surface substrate failure or partial delamination (Figure B-7). The average pull-off strength was 155.6 psi. Since the average strength is above 150 psi, the Epoxy-substate bond strength is good.

Figure B-7. Pull-Off Test for Specimen 17-3.

Site 28 – Core 1: Thermoplastic Treatment Age: 5 years; DGFC Substrate Age: 5 years

The research team determined that the failure mechanism for this specimen was 100% substrate failure(HMA to HMA bond) (Figure B-8). The average strength at failure (87.4 psi) was relatively very low (<150 psi). Because of the failure mechanism and low strength, an additional surface pull-off test is needed (on a sample with a shallow groove). At the current state, the thermoplastic-substate bond strength is inconclusive.

Figure B-8. Pull-Off Test for Specimen 28-1.

Site 20 – Core 2-4: Epoxy Treatment Age: 2.5 years; OGFC Substrate Age: 2.5 years

Figure B-9, Figure B-10 and Figure B-11 show cores number 2, 3, and 4, respectively, collected from site 20. The cores are Epoxy-treated-OGFC. Cores 2 and 4 show that the epoxy penetrated the substrate voids. Meanwhile, there was no penetration in Core 3 (maybe due to different application methods, e.g., squeegee vs. spray). Moreover, core-3 was severely cracked, and almost no effort was needed to break up the sample under the pull-off test (weaker substrate?). In general, the cores from section 20 offered very low resistance force (<<150 psi) to pull off test force (Table B1). The research determined that the failure mechanism for this specimen was 100% OGFC failure. Additional tests on a shallowly grooved sample may be needed to assess Epoxy-substrate bond strength separately.

Figure B-9. Pull-Off Test for Specimen 20-2.

Figure B-10. Pull-Off Test for Specimen 20-3.

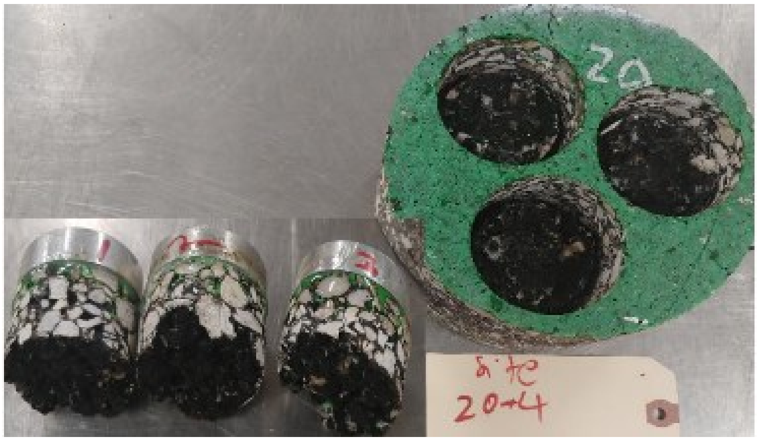

Figure B-11. Pull-Off Test for Specimen 20-4.

Site 18 – Core 1-3: Epoxy Treatment Age: 2 years; OGFC/DGFC Substrate Age: 3 years

Figure B-12, Figure B-13 and Figure B-14 show cores number 1, 2, and 3, respectively, collected from site 18. Cores 1 and 2 are Epoxy-treated-OGFC, whereas Coore-3 is Epoxy-treated-DGFC. During the pull-off test, the research team observed that the failures for all three cores were 100% substrate and the strength at failure was below 150 psi. Therefore, the research team determined that the Epoxy-substrate bond strength is inconclusive based on the failure mechanism and low strength. Future tests will include shallowly grooved specimens to specify GCPM bond strength separately.

Figure B-12. Pull-Off Test for Specimen 18-1.

Figure B-13. Pull-Off Test for Specimen 18-2.

Figure B-14. Pull-Off Test for Specimen 18-3.

Site 7 – Core 1 and 3: Epoxy Treatment Age: 3 years; DGFC Substrate Age: 3 years

Figure B-15 and Figure B-16 show cores 1 and 3 collected from site 7. All cores are Epoxy-treated-DGFC. Core-1 was extracted from the surface of a cracked shoulder (Site 7NB). At the same time, core-3 was pulled from an excellent location next to the turning lane. Laboratory investigation shows that core-1 has an existing horizontal fissure under the surface. Therefore, no effort was needed to pull off the layer. The failure was 100% substrate failure. Similarly, core-3, which was extracted from the bike lane next to a turning lane (good location), yielded high pull-off strength (204.6 psi>150psi).

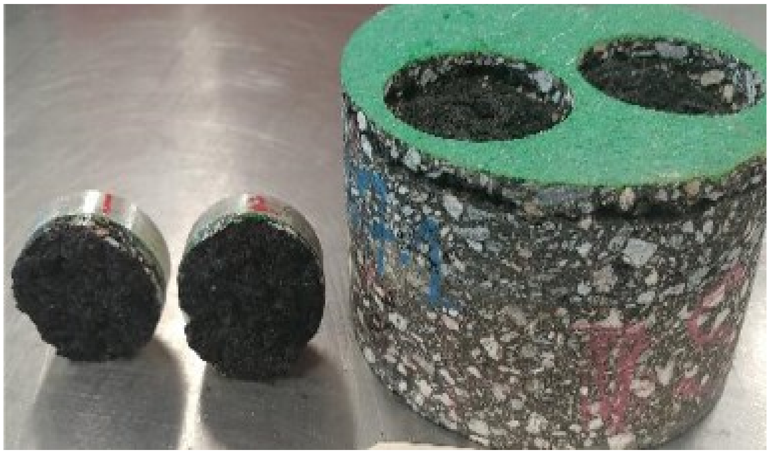

Figure B-15. Pull-Off Test for Specimen 7-1.

Figure B-16. Pull-Off Test for Specimen 7-3.

Site 26 – Core 1: Thermoplastic Treatment Age: 1.5 years; DGFC Substrate Age: 1.5 years

Figure B-17 shows core-1 collected from site 26. During the pull-off test, the researchers observed a failure at the very bottom of the DGFC substrate. And the pull-off force that failed the specimen was below 150 psi. Because of this failure mechanism, the research team determined that the GCPM bond strength is inconclusive, pending additional tests on shallow cut surface to specify GCPM bond strength separately.

Figure B-17. Pull-Off Test for Specimen 26-1.

Site 7 – Core 6: Epoxy Treatment Age: 3 years; DGFC Substrate Age: 3 years

By predetermining the failure location (on shallowly grooved specimens), the research team demonstrated that one could force surface delamination to determine the GCPM-Substrate bond strength without worrying about failure at different locations—nevertheless, the technique sacrifices the assessment of substrate strength. Figure B-18 shows core-6 collected from site 7. The specimen is an Epoxy-treated-DGFC core. Based on the pull-off test, the average strength of the epoxy DGFC bond was 280.85psi. It passed the minimum cut-off value (150 psi).

Figure B-18. Pull-Off Test for Specimen 7-6.

Site 17 – Core 1: Epoxy Treatment Age: 2 years; DGFC Substrate Age: Slightly older

The forced delamination was also demonstrated on Site 17 cores. Figure B-19 shows core-1 collected from site 17. The specimen is an Epoxy-treated-DGFC core. Based on the pull-off test, the average strength of the epoxy to DGFC bond was 197.4 psi. It passed the minimum cut-off value (150 psi).

Figure B-19. Pull-Off Test for Specimen 17-1.

APPENDIX C
GCPM STAKEHOLDER QUESTIONNAIRE

Green-Colored Pavement Markings - Industry and Agency Interview Questions

10/23/2020

Question Key

S - Supplier

C - Contractor

A - Agency (State)

General

- Interviewee Name:
- Interviewee Title:
- Company/Agency Name:
- Product Name:

Product/Materials

- A. Which Green Colored Pavement Marking (GCPM) products are approved in your agency?
- A. Which GCPM products are not approved in your agency?
- SC. What are the components of ___product___?
    - Binding agent, friction components, pigment, other?
- S. Have you had any issues with raw components?
    - (e.g. few/foreign sources, high cost, variable quality)
- A. What are the material/performance requirements that a product must meet for approval (be specific)?
    - Chromaticity (x,y), and Luminance (Y)
    - Friction
    - Durability
    - Other
- A. Are you considering any other material or performance requirements, or modifications to the criteria or test methods?

- SC. What challenges do you face trying to meet material/performance requirements?
    - Chromaticity (x,y), and Luminance (Y)
    - Friction
    - Durability
    - Other
- C. Do you do any in-house testing of ___product___ or is it good enough that it made the approved-product list?
- S. Are there any other test methods/material properties that agencies should consider when approving GCPM materials?
- SC. What is the typical unit cost of ___product___?

Design

- A. Do you have standard plans or design criteria associated with green-colored pavement markings?

Construction

- SCA. What is the usual relationship between supplier and contractor?
    - Same company/sister companies?
    - Does contractor need high specialization?
- SCA. What are the surface preparation procedures for ___product___?
    - Critical issues to watch for.
- SCA. What is the application process for ___product___?
    - Application methods: E.g. Heat applied, rolled, sprayed, squeegee.
        - Target thickness
        - Installation Procedures
        - Production rates and cure times
- SCA. How do these procedures change when you're working with different substrates?
    - Dense-grade HMA
    - Open-grade HMA
    - Concrete
- SCA. Any other problems encountered during construction?
- A. Does your agency have acceptance criteria for construction? Describe.

- A. Is your agency considering alterations to the construction specifications/acceptance criteria?

Performance

- SCA. What is the typical service life of ___product___?
- A. Does your agency monitor the performance of your GCPM installations?
- SCA. How does the color performance of ___product___ change over time?
- SCA. How does the friction performance of ___product___ change over time?
- SCA. What kinds of distresses have you observed with ___product___? What do you believe causes these distresses?
- A. How common are these distresses?

Maintenance/Repair/Replacement

- CA. Have you done any maintenance (cleaning) on GCPMs? How effective was this?
- CA. What are the procedures for maintaining/repairing/replacing ___product___?

Experience on National Level

- SC. How does Florida's approach to GCPM experience compare to approaches by other states?
- SC. Are states or cities driving the use of GCPM more?
- CA. Do states and cities have different approaches to applying GCPM?
  - Note in Florida that cities had long installations in urban centers, while states had "spot" applications just at conflict locations, conforming to the MUTCD.
- SC. Which states/cities are the biggest players of GCPM?
- SCA. Do you expect growth, steadiness, or decline in the GCPM market?

APPENDIX D

ACCELERATED WEATHERING REFERENCES

The development of an accelerated weathering method for green bike lane materials needs to consider the evaluation's settings, cycles, and duration. More extended evaluations and aggressive environments will result in more wear to the test samples. FDOT needs to decide what estimated level of typical outdoor weathering they want to simulate with the accelerated weathering. For example, 1000 hours (1.37 months) of accelerated weathering described in of ASTM D4956, Supplementary Requirement S3.3.2-Method 1 (ASTM, 2019) or D7869 would result in approximately 6.8 months and 6 months respectively of simulated outdoor exposure. Shorter accelerated weathering exposures would result in shorter simulated outdoor exposure levels. Tables D-1 and D-2 provide the developed accelerated weathering factors and the relationship between the duration of accelerated and the resulting controlled outdoor weathering. The table provides a range of accelerated weathering duration and the resulting quantity of simulated outdoor weathering that results. If FDOT wants to simulate at least 3 months of outdoor weathering at least 500 hours of accelerated weathering will need to occur no matter which method and settings are used for the accelerated weathering.

Table D-1. Wear Factor of Accelerated Weathering.

Accelerated Wear Factor Based on UV Radiation			
D4956 Method I	D4956 Method II	D7869	Modified D 7869
5	3.4	4.4	6.1

Table D-2. Relationship of Accelerated Weathering to Controlled Outdoor Weathering.

Accelerated Weathering Duration, hours (months)	Outdoor Weathering, hours (months)			
	D4956 Method I	D4956 Method II	D7869	Modified D 7869
2000 (2.7)	10000 (13.7)	6800 (9.3)	8800 (12.1)	12200 (16.7)
1000 (1.4)	5000 (6.8)	3400 (4.7)	4400 (6.0)	6100 (8.4)
500 (0.7)	2500 (3.4)	1700 (2.3)	2200 (3.0)	3050 (4.2)
250 (0.3)	1250 (1.7)	850 (1.2)	1100 (1.5)	1525 (2.1)
100 (0.1)	500 (0.7)	340 (0.5)	440 (0.6)	610 (0.8)

ASTM D7869 (ASTM, 2013) is a relatively new standard that has not been widely used on traffic control devices. Modifications to the standard such as those recommended in FDOT report

BE717 have not been tested on green bike lane materials or tested on pavement markings as far as can be found. Based on that, it is recommended to use the more widely used and studied ASTM G155 (ASTM 2013) cycle 1 or the variations of it used in ASTM D4956 method I or II (ASTM, 2019). ASTM G155 is described in Figures D-1 through D-3. The method I will provide a higher rate of accelerated wear on the samples. It is recommended for this initial study on green bike lane material to study the materials, or at least some of them across a range of accelerated wear durations, so that the impact can be evaluated. It is recommended to assess the samples new and then after 100, 250, and 500 hours of accelerated weathering. This will allow the results to be evaluated such that a future may only need to use one of the accelerated weathering durations.

X3. EXPOSURE CONDITIONS

X3.1 Any exposure conditions may be used, as long as the exact conditions are detailed in the report. Following are some representative exposure conditions. These are not necessarily preferred and no recommendation is implied. These conditions are provided for reference only (see Table X3.1).

NOTE X3.1—These exposure conditions are brief summaries of the actual exposure procedures. Consult the applicable test method or material specification for detailed operating instructions and procedures. Historical convention has established Cycle 1 as a very commonly used exposure cycle. Other cycles may give a better simulation of the effects of outdoor exposure. Cycle 3 has been used for exterior grade textile materials. Cycle 4 has been used for indoor plastics. Cycles 5 and 6 have been commonly used for indoor textile materials. Cycle 7 has been used for automotive exterior materials. Cycle 8 has been used for automotive interior components.

NOTE X3.2—Cycle 7 corresponds to the test cycles specified in SAE J2527. Cycle 8 corresponds to the test cycles specified in SAE J2412. Consult the appropriate test procedure for detailed cycle descriptions, operating instructions, and a description of the filters used in this application. The filter system specified in these procedures is characterized in 6.1.4.

NOTE X3.3—More complex cycles may be programmed in conjunction with dark periods that allow high relative humidities and the formation of condensate at elevated chamber temperatures. Condensation may be produced on the face of the specimens by spraying the rear side of the specimens to cool them below the dew point.

NOTE X3.4—For special tests, a high operating temperature may be desirable, but this will increase the tendency for thermal degradation to adversely influence the test results.

NOTE X3.5—Surface temperature of specimens is an essential test quantity. Generally, degradation processes accelerate with increasing temperature. The specimen temperature permissible for the accelerated test depends on the material to be tested and on the aging criterion under consideration.

NOTE X3.6—The relative humidity of the air as measured in the test chamber is not necessarily equivalent to the relative humidity of the air very close to the specimen surface. This is because test specimens having varying colors and thicknesses may be expected to vary in temperature.

X3.2 Unless otherwise specified, operate the apparatus to maintain the operational fluctuations specified in Table X3.2 for the parameters in Table X3.1. If the actual operating conditions do not agree with the machine settings after the equipment has stabilized, discontinue the test and correct the cause of the disagreement before continuing.

NOTE X3.7—Set points and operational fluctuations could either be listed independently of each other, or they could be listed in the format: Set point ± operational fluctuations. The set point is the target condition for the sensor used at the operational control point as programmed by the user. Operational fluctuations are deviations from the indicated set point at the control point indicated by the readout of the calibrated control sensor during equilibrium operation and do not include measurement uncertainty. At the operational control point, the operational fluctuation can exceed no more than the listed value at equilibrium. When a standard calls for a particular set point, the user programs that exact number. The operational fluctuations specified with the set point do not imply that the user is allowed to program a set point higher or lower than the exact set point specified..

X3.3 For conversion of test cycles from G26 to G155 see Table X3.3.

Figure D-1. ASTM G155 Exposure Conditions Overview. (ASTM, 2013)

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TABLE X3.1 Common Exposure Conditions

Cycle	Filter	Irradiance	Wavelength	Exposure Cycle
1	Daylight	0.35 $W/(m^2 \cdot nm)$	340 nm	102 min light at 63°C black panel temperature 18 min light and water spray (air temp. not controlled)
2	Daylight	0.35 $W/(m^2 \cdot nm)$	340 nm	102 min light at 63°C black panel temperature 18 min light and water spray (air temp. not controlled) repeated nine times for a total of 18h; followed by 6 h dark at 95 (±4.0) % RH, at 24°C black panel temperature
3	Daylight	0.35 $W/(m^2 \cdot nm)$	340 nm	1.5 h light, 70 % RH, at 77°C black panel temperature 0.5 h light and water spray (air temp. not controlled)
4	Window Glass	0.30 $W/(m^2 \cdot nm)$	340 nm	100 % light, 55 % RH, at 55°C black panel temperature
5	Window Glass	1.10 $W/(m^2 \cdot nm)$	420 nm	102 min light, 35 % RH, at 63°C black panel temperature 18 min light and water spray (air temp. not controlled)
6	Window Glass	1.10 $W/(m^2 \cdot nm)$	420 nm	3.8 h light, 35 % RH, at 63 °C black panel temperature 1 h dark, 90 % RH, at 43 ° C black panel temperature
7	Extended UV	0.55 $W/(m^2 \cdot nm)$	340 nm	40 min light, 50 % RH, at 70 (±2) °C black panel temperature and 47 (±2) °C chamber air temperature 20 min light and water spray on specimen face 60 min light, 50 % RH, at 70 (±2) °C black panel temperature; and 47 (±2) °C chamber air temperature 60 min dark and water spray on specimen front and back, 95 % RH, 38 (±2) °C black panel temperature and 38 (±2) °C chamber air temperature
7A	Daylight	0.55 $W/(m^2 \cdot nm)$	340 nm	40 min light, 50 (±5.0) % RH, at 70 (±2) °C black panel temperature and 47 (±2) °C chamber air temperature 20 min light and water spray on specimen face; 60 min light, 50 % RH, at 70 (±2) °C black panel temperature; and 47 (±2) °C chamber air temperature 60 min dark and water spray on specimen front and back, 95 % RH, 38 (±2) °C black panel temperature and 38 (±2) °C chamber air temperature
8	Extended UV	0.55 $W/m^2 \cdot nm$	340 nm	3.8 h light, 50 % RH, at 89 (±3) °C black panel temperature and 62 (±2) °C chamber air temperature 1.0 h dark, 95 % RH, at 38 (±2) °C black panel temperature and 38 (±2) °C chamber air temperature
9	Daylight	180 W/m^2	300–400 nm	102 min light at 63°C black panel temperature 18 min light and water spray (temperature not controlled)
10	Window Glass	162 W/m^2	300–400 nm	100 % light, 50 % RH, at 89°C black panel temperature
11	Window Glass	1.5 $W/(m^2 \cdot nm)$	420 nm	Continuous light at 63°C black panel temperature, 30 % RH
12	Daylight	0.35 $W/(m^2 \cdot nm)$	340 nm	18 h consisting of continuous light at 63°C black panel temperature 30 % RH 6 h dark at 90 % RH, at 35°C chamber air temperature

Figure D-2. ASTM G155 Exposure Cycles. (ASTM, 2013)

X2. EXPOSURE CONDITIONS

X2.1 Any exposure conditions may be used, as long as the exact conditions are detailed in the report. Following are exposure conditions taken from several material test methods. These are not necessarily preferred and no recommendation is implied. These conditions are provided for reference only (see Table X2.1).

NOTE X2.1—This information is provided for historical reference only. It is not intended to be comprehensive or current, nor should it be relied upon for any specific end use application.

NOTE X2.2—When selecting programs of UV exposure followed by condensation, allow at least 2 h per interval to assure attainment of equilibrium.

NOTE X2.3—Surface temperature of specimens is an essential test quantity. Generally, degradation processes accelerate with increasing temperature. The specimen temperature permissible for the accelerated test depends on the material to be tested and on the aging criterion under consideration.

NOTE X2.4—Irradiance data shown is typical.

NOTE X2.5—The light output of fluorescent lamps is affected by the temperature of the air which surrounds the lamps. Consequently, in apparatuses without feed-back-loop control of irradiance, the lamp output will decrease with increasing chamber temperature.

NOTE X2.6—Laboratory ambient temperature may have an effect on the light output of devices without feed-back-loop control of irradiance. Some fluorescent UV devices use laboratory ambient air to cool the lamps and thereby compensate for the drop in light output at higher exposure temperatures (see Note X2.5).

X2.2 For the most consistent results, it is recommended that apparatus without feed-back-loop control of irradiance be operated in an environment in which the ambient temperature is maintained between 18 and 27°C. Apparatus operated in ambient temperatures above or below this range may produce irradiances different from devices operated in the recommended manner.

NOTE X2.7—Fluorescent UV lamps emit relatively little infrared radiation when compared to xenon arc and carbon arc sources. In fluorescent UV apparatus, the primary heating of the specimen surface is by convection from heated air passing across the panel. Therefore, there is a minimal difference between the temperature of an insulated or uninsulated black or white panel thermometer, specimen surface, air in the test chamber, or different colored samples (3).

X2.3 For operational fluctuations, see Table X2.2.

NOTE X2.8—Unless otherwise specified, operate the apparatus to maintain the operational fluctuations specified in Table X2.2 for the parameters in Table X2.1. If the actual operating conditions do not agree with the allowed fluctuations from the machine settings after the equipment has stabilized, discontinue the test and correct the cause of the disagreement before continuing.

TABLE X2.1 Some Historical Exposure Conditions

Cycle	Lamp	Typical Irradiance	Approximate Wavelength	Exposure Cycle	Original Reference and Application, Where Known
1	UVA-340	0.89 W/(m² • nm)	340 nm	8 h UV at 60 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature	D4329 cycle A for general Plastics; D4587 Cycle 4 for general metal coatings; C1442 for sealants
2	UVB-313	0.71 W/(m² • nm)	310 nm	4 h UV at 60 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature	Unknown
3	UVB-313	0.49 W/(m² • nm)	310 nm	8 h UV at 70 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature	SAE J2020
4	UVA-340	1.55 W/(m² • nm)	340 nm	8 h UV at 70 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature	Unknown
5	UVB-313	0.62 W/(m² • nm)	310 nm	20 h UV at 80 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature	Unknown
6	UVA-340	1.55 W/(m² • nm)	340 nm	8 h UV at 60 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature.	Unknown
7	UVA-340	1.55 W/(m² • nm)	340 nm	8 h UV at 60 (±3) °C Black Panel Temperature; 0.25 h water spray (no light), temperature not controlled; 3.75 h condensation at 50 (±3) °C Black Panel Temperature	Unknown
8	UVB-313	28 W/m²	270 to 700 nm	8 h UV at 70 (±3) °C Black Panel Temperature; 4 h Condensation at 50 (±3) °C Black Panel Temperature	Unknown

Figure D-3. ASTM G154 Exposure Condition Overview and Exposure Cycles.

(ASTM 2013).