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Evaluation of Recycled Plastic Modified Asphalt Mixtures and Pavements: Phase I - A Case Study in Virginia

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16. Abstract:

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The four mixtures were evaluated in terms of durability, dynamic modulus, resistance to rutting, and resistance to cracking using multilevel performance tests (basic, intermediate, and advanced). All the observations indicated that RPM mixtures can demonstrate similar durability and better rutting and cracking performance properties compared with D mixtures. However, the observations, when compared with E mixtures, suggest that the resistance to cracking might have decreased for RPM mixtures with long-term aging. Furthermore, representative samples of RPM mixtures were generated and subjected to solvent extraction and gradation, followed by thermogravimetric and infrared testing to assess and quantify (if possible) the presence of microplastics. Overall, the findings were that solvent extraction followed by thermogravimetric and infrared testing could be an effective method for identifying and quantifying discrete plastic particles present in artificially abraded RPM asphalt mixtures modified with recycled polyethylene. However, this extraction method is not suitable for RPM asphalt mixtures modified with Polyethylene Terephthalate-based additives. Furthermore, it is still uncertain whether these particles are released into the environment under typical wear and tear of the pavement.

The study recommends that VDOT consider allowing the use of RPM surface mixtures as another alternative for surface mixtures with D designation based on the laboratory performance of corresponding asphalt mixtures. As explained in the implementation section, a stakeholder group should develop a roadmap to address questions related to this recommendation. Because the sections evaluated in this study were placed in 2021, the 2-year performance data and corresponding observations are still considered preliminary. Continued monitoring of field performance will be needed to quantify more accurate benefits of including recycled plastics in asphalt mixtures compared with regular unmodified and styrene-butadiene-styrene-modified surface mixtures. The study also recommends additional field trials with RPM mixtures for further performance and benefit-cost evaluation, as well as life-cycle assessment. Furthermore, this study also recommends pursuing opportunities for research to apply the microplastic analysis methods developed during this study to field samples to investigate further the use of performance-based testing to design RPM mixtures and to explore necessary steps to repurpose plastic waste generated in Virginia and engineer it for responsible inclusion in asphalt mixtures.

Supplemental files can be found at https://library.vdot.virginia.gov/vtrc/supplements

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FINAL REPORT

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ABSTRACT

The purpose of this study was to assess recycled plastic-modified (RPM) asphalt mixtures field trials constructed in Virginia. This study documented and evaluated the constructability and laboratory performance of two plant-produced RPM mixtures compared with the Virginia Department of Transportation (VDOT) typical D and E surface mixtures as reference mixtures. D and E refer to medium to high and high to extremely high traffic, respectively. No changes from the established routine practices in terms of surface preparation, plant production, or paving operations were reported. Moreover, this study attempted to detect and quantify the presence of microplastics in material generated from pavement wear that could potentially be mobilized via stormwater runoff. As RPM asphalt mixtures are novel materials, this objective includes the identification and development of appropriate laboratory analysis methods for microplastics. Overall, this effort is among the first and few to document findings and lessons learned regarding the incorporation of recycled plastic into asphalt mixtures through field trials.

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INTRODUCTION

With the change in recycling streams over the past few years, there has been a growing interest among highway agencies in diverting plastics from the waste stream for reuse in asphalt mixtures. In 2017, plastics accounted for 35.4 million tons of waste in the United States, with only 3 million tons (8% of the plastic waste) being recycled, 5.6 million tons (16% of the plastic waste) undergoing combustion, and a significant 26.8 million tons (76% of the plastic waste) being stacked and landfilled. This situation has raised critical concerns about plastic waste management (Habbouche, 2022; Willis et al., 2020; Yin et al., 2020). A review of the literature identified seven types of plastics with various chemical and physical properties. These plastics are identified by resin identification codes in accordance with the standard of the American Chemistry Council (ACC). Table 1 shows a summary of these codes (Willis et al., 2020; Yin et al., 2020).

Table 1. Plastics: Types, Applications, and Uses.

RIC	Types of Plastics	Application/Uses
1	Polyethylene Terephthalate (PET)	Bottles for water and soda; food packaging; food containers
2	High Density Polyethylene (HDPE)	Plastic mailing envelopes; flexible pipes; plastic chairs/stools; toys and playground equipment; plastic bags; shampoo bottles
3	Polyvinyl Chloride (PVC)	Pipes; electric cables; construction material; sign boards; vinyl flooring
4	Low Density Polyethylene (LDPE)	Trays and containers; plastic wraps; plastic bags; Juice and milk containers
5	Polypropylene (PP)	Plastic hinges; piping system; plastic chairs; reusable plastic containers; plastic moldings
6	Polystyrene (PS)	Food packaging; CD and DVD casing; disposable utensils; license plate frames; foam beverage cups
7	Other (Polycarbonate—PC; Polylactide—PLCA; Acrylonitrile Butadiene Styrene—ABS; Nylon; Fiberglass; Acrylic)	Baby bottles; car parts; water cooler bottles; food containers

RIC = resin identification code
Source: Willis et al. (2020), modified by the authors

Researchers and engineers have begun exploring the potential of using asphalt mixtures as a suitable medium to incorporate recycled plastic (or plastic waste). Although the body of literature on this subject is growing, many documented efforts lack a clear experimental plan and rely on outdated test methods. In addition, it remains uncertain whether producing and paving asphalt mixtures modified with recycled plastic, referred to herein as recycled plastic modified (RPM) asphalt mixtures, would require any changes to typical paving practices, especially to those in Virginia (Habbouche, 2022).

In light of these challenges, additional research was recommended, with a particular focus on various aspects (Habbouche, 2022; Willis et al., 2020; Yin et al., 2020). These aspects include sourcing and methods of incorporating recycled plastics, material characterization of laboratory- and field-produced RPM asphalt mixtures, plant operations, health and safety considerations, and most importantly, the construction of field demonstration projects to assess short- and long-term performance (Willis et al., 2020; Yin et al., 2020).

The Virginia Department of Transportation (VDOT) has been considering the initiative of incorporating recycled plastics into asphalt mixtures for several years. This initiative aims to provide a sustainable solution to enhance the performance of asphalt mixtures in Virginia. Moreover, this initiative may help divert waste plastics from landfills and/or use them as a commodity replacement for other raw materials.

However, with an increased interest in the reuse of waste plastics, there is a growing concern about the presence of microplastics in the environment. The U.S. Environmental Protection Agency defines microplastics as any plastic particle with a diameter of 5 mm or smaller (Murphy, 2017). These particles typically result from the breakdown of larger plastic pieces and have been found to accumulate in surface waters, sediments, and beach sands. They can have adverse effects on aquatic and terrestrial organisms, as well as human health, due to ingestion and the release of chemicals, including phthalates, during degradation.

The level of concern regarding microplastics has led to legislative action. In 2018, the State of California passed legislation (Senate Bill No. 1422 California Safe Drinking Water Act: microplastics) that requires the adoption of a definition for microplastics and the development of testing procedures for microplastics in drinking water by July 1, 2021 (CA Senate Bill No. 1422, 2018). The definition adopted by California states that: "Microplastics in Drinking Water are defined as solid polymeric materials to which chemical additives or other substances may have been added, which are particles which have at least three dimensions that are greater than 1nm and less than 5,000 µm. Polymers that are derived in nature that have not been chemically modified (other than by hydrolysis) are excluded" (California Water Board, 2020).

In response to these concerns, several procedures have been developed to identify and quantify microplastics in water, soil, and sand. However, a dearth of information is currently available regarding the association between the use of RPM asphalt mixtures and the generation or release of microplastics into the environment.

To support the current state of knowledge and assess the feasibility of using RPM asphalt mixtures as a sustainable solution for enhancing the performance of asphalt pavements and reducing plastic waste in the United States, the construction of field trials was highly recommended.

PURPOSE AND SCOPE

The purpose of this study was to assess RPM field trials constructed in Virginia. This was achieved by documenting, benchmarking, and evaluating the constructability, laboratory performance, predicted long-term performance by means of mechanistic-empirical (ME) simulations, and initial field performance of RPM asphalt mixtures, in comparison with VDOT typically unmodified D mixtures and E mixtures modified with conventional styrene-butadiene-styrene (SBS) elastomer (reference mixtures). D and E refers to medium to high and high to extremely high traffic, respectively. A second objective of this study was to assess the impact of testing on the performance properties of RPM mixtures and their corresponding reference mixtures (unmodified and SBS-modified asphalt mixtures), based on degree of complexity—basic, intermediate, or advanced. The third objective of this study was to attempt to detect and quantify the presence of microplastics in material generated from pavement wear. As RPM asphalt mixtures are relatively novel, this objective included the identification and development of appropriate laboratory analysis methods for microplastics. This effort is among the first and few to document findings and lessons learned regarding the incorporation of recycled plastic into asphalt mixtures through field trials. The evaluation of cost-effectiveness and life-cycle assessment of incorporating recycled plastics into asphalt mixtures were beyond the scope of this study, due to limitations in available data.

METHODS

The research team performed eight tasks to achieve the study objectives:

1. Document the project selection, mix design, production, and construction processes of unmodified, SBS-modified, and RPM mixtures.

2. Sample virgin asphalt binders, recycled plastics, and plant-produced loose asphalt mixtures; obtain producer-supplied specimens compacted during production (referred to herein as "non-reheats"), and collect as-paved material (i.e., cores) during construction.

3. Conduct extensive performance testing on asphalt binders modified with recycled plastics at various contents in the laboratory, on virgin asphalt binders sampled at the plant, and on asphalt binders extracted and recovered from loose mixtures sampled at the plant during production.

4. Conduct volumetric and multilevel laboratory performance testing on specimens fabricated from non-reheated (i.e., non-reheats) and reheated (referred to herein as "reheats") plant-produced mixtures and perform analyses to evaluate the mixtures.

5. Conduct ME simulations using FlexPave to predict the long-term performance of the RPM, unmodified, and SBS-modified reference mixtures when placed on typically encountered pavement structures in Virginia.

6. Conduct non-destructive testing using a falling weight deflectometer (FWD), ground-penetrating radar (GPR), and a profilometer to assess the overall pavement structure after paving and the impact of adding recycled plastics to asphalt mixtures on roughness and macrotexture.

7. Conduct a visual surface distress survey and collect data from VDOT's Pavement Management System (PMS) to assess the in-service conditions of the pavement structures.

8. Generate representative samples and subject them to solvent extraction and gradation, followed by thermogravimetric and infrared testing to assess and quantify (if possible) the presence of microplastics.

Field Trials

One major benchmarking experiment/project was planned, developed, and constructed during VDOT's 2021 construction season. The experiment included four mixtures with a nominal maximum aggregate size (NMAS) of 12.5 mm:

- One typical surface mixture (SM) is "SM-12.5D," a reference mixture (VDOT typical mixture produced with unmodified asphalt binder and designed for traffic loads of 3 to 10 million equivalent single axle loads [ESALs]).
- One typical "SM-12.5E" reference mixture (VDOT typical mixture produced with SBS-modified asphalt binder formulated using ~3.5% SBS content and designed for traffic loads of 10 to 30 million ESALs).
- Two RPM mixtures (referred to herein as "SM-12.5RPM").
    - The first RPM mixture featured the use of a complex arrangement of polyethylene-based polymers, denoted as "P1" and shown in Figure 1a, designed to extend and enhance asphalt binders used for road surfaces, at a rate of 5% by total weight of the employed asphalt binder (no binder replacement). This mixture is referred to as "SM-12.5RPM P1."
    - The second plastic trial featured the use of polyethylene terephthalate PET-based plastomeric amorphous polymers, denoted as "P2" and shown in Figure 1b, with the aim of improving the overall performance of the asphalt mixture, at a rate of 3% by total weight of the employed asphalt binder (full binder replacement). This mixture is referred to as "SM-12.5RPM P2."

Both recycled plastic products are engineered and proprietary. The specific composition of each product was not disclosed to the research team. The RPM mixtures were designed to meet the agency's specifications in terms of gradations and volumetric properties (VDOT, 2020). SM-12.5D and SM-12.5E included 30% and 15% reclaimed asphalt pavement (RAP) contents, respectively.

(a) (b)

Figure 1. Photographs Taken of Recycled Plastic Products: (a) P1; (b) P2

Meanwhile, both RPM mixtures included 15% RAP content and were produced using a PG 64S-22 asphalt binder. In this context, PG indicates performance grade and "S" denotes binders meeting the requirement of standard traffic, using the multiple stress creep recovery (MSCR) test in accordance with AASHTO M 332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test (AASHTO, 2020).

The contents of recycled plastics products were determined through binder and mixture testing at various levels for SM-12.5RPM P1, whereas for SM-12.5RPM P2, the determination was based solely on mixture testing at various recycled plastic contents.

The mixtures were produced following typical contractor practices. The only difference was that the recycled plastics were added to the mixtures following a "dry process." The plastics were introduced at the RAP collar behind the flame at the target rates, using carefully calibrated fiber feeders to ensure a consistent flow of plastic (Figure 2). Then they were mixed with the hot aggregates prior to introducing the asphalt binder. The E and RPM mixtures were produced within a temperature range of 320°F to 330°F.

About 700 tons of each of the three mixtures, SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2, were produced and placed in a 1.5-inch single lift over the course of 1-mile-long adjacent stretches on Old Stage Road in Chester, VA, (from Route 10, Iron Bridge Road to Route 615, Conondale Road) as Figure 3 shows. The remainder of this route was paved with a typical SM-9.5D per the initial contract. However, the laboratory and field performances of this mixture (i.e., SM-9.5D) were not evaluated in this study. This route was selected from VDOT's 2021 paving contracts and in a way that the long-term performance could be monitored and evaluated in the future. The SM-12.5D mixture, evaluated in this study, was produced within a temperature range of 280°F to 300°F and was placed in the field in a nearby location within the Chester area as part of a separate contract (i.e., Route 600). This mixture was selected as a reference mixture due to its identical NMAS, the use of the same virgin asphalt binder, and a gradation similar to that of the RPM asphalt mixtures. Table 2 summarizes the VDOT RPM field trials constructed during the 2021 construction season (Habbouche, 2022).

(a) (b)

Figure 2. Photographs Taken of Feeder Machines Used for Recycled Plastic Products: (a) P1; (b) P2

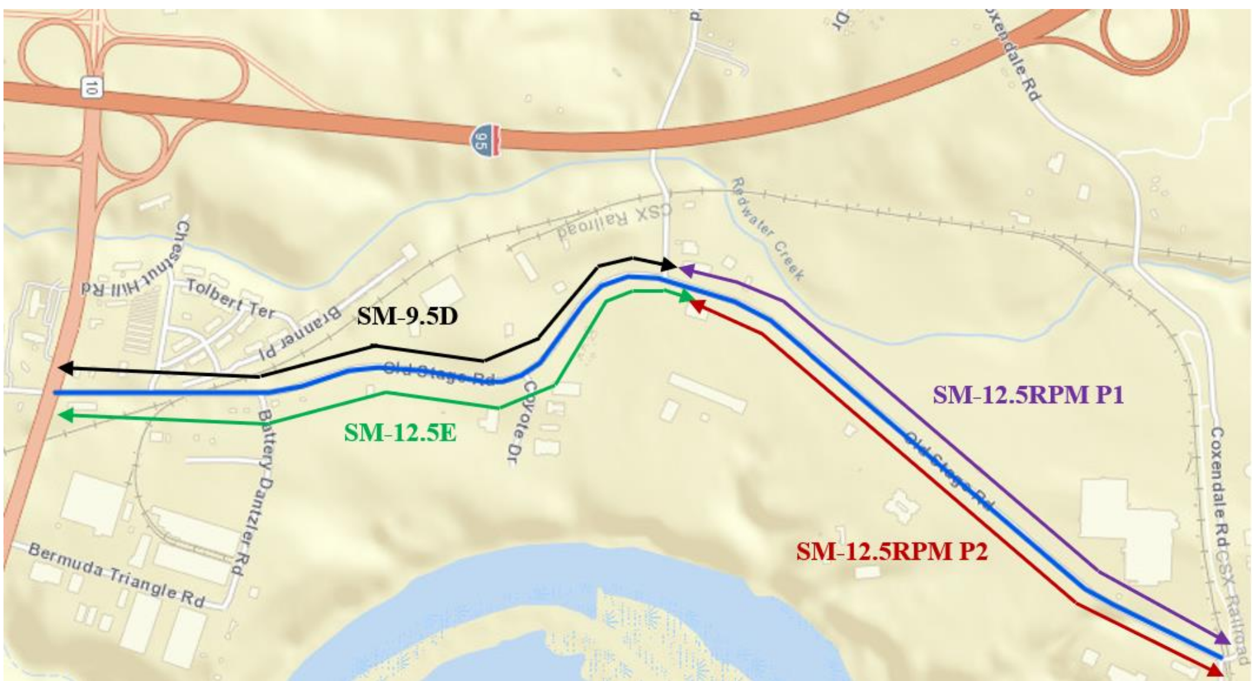


Figure 3. Locations of Asphalt Field Trial Recycled Plastic Modified and Reference Mixtures. SM = surface mixture; D = mixture designation; RPM = recycled plastic modified; E = extremely heavy traffic.

Table 2. Recycled Plastic Modified Asphalt Field Trial Mixtures (2021 Construction Season)

Year	Mix Type	Location
2021	SM-12.5D: 30% RAP + PG 64S-22	Route 600
	SM-12.5E: 15% RAP + PG 64E-22 (~3.5% SBS by weight of virgin binder)	Old Stage Road, Chester, Richmond, VA (PM-4F-21)
	SM-12.5RPM P1: 15% RAP + PG 64S-22 + P1 (~5% by total weight of binder)	
	SM-12.5RPM P2: 15% RAP + PG 64S-22 + P2 (~3% by total weight of binder)	

SM = surface mixture; D = VDOT mixture designation for 3–10 million equivalent single axle load traffic; E = extremely heavy traffic; RAP = reclaimed asphalt pavement; PG = performance grade; SBS = styrene-butadiene-styrene; RPM = recycled plastic modified.

The preconstruction conditions of the selected roadway site were documented, using VDOT's PMS and a field visit / visual review. Notes/details relevant to the production and lay-down / paving operations were documented. Photographs were taken during production at the plant and during paving operations in the field; some are shown in Figure 4. The first few tons of SM-12.5RPM P1 were produced at a relatively low temperature (~290°F to 300 °F), resulting in the initial roller pattern and control strip not meeting the density specifications. The reason could be due to the slight increase in stiffness of produced asphalt mixtures when recycled plastic particles were included. Furthermore, the temperature in the field was slightly cooler than usual for the time of the year (first cool night of the year). To account for the effects of the cool weather, the production temperature of asphalt mixtures at the plant was increased to ~325°F. As the night progressed, all core densities passed the required density specifications. The first night of trials generated several lessons learned. No issues were encountered when producing and paving the SM-12.5RPM P2. No changes from routine established practices in relation to surface preparation or paving operations were reported; standard construction practices and equipment were used (Habbouche, 2022).

Figure 4. Photographs Taken for Production Operations at the Plant and Paving/Construction in the Field for RPM and Reference Mixtures

Material Sampling and Specimen Designations

Each of the three mixtures, SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2, was produced over a single night (on three separate nights). Meanwhile, SM-12.5D was produced for multiple nights. Loose mixture sampling was performed once during each night of production for SM-12.5E, SM-12.5RPM P1, and SM-12.5 RPM P2, and once during one of the multiple nights of production for SM-12.5D.

Plant-produced loose mixtures were collected for each mixture type. Loose mixtures were sampled from an approximately 3- to 5-ton quantity of mixture dumped on the ground at the plant and leveled using a loader. Loose plant-produced mixture intended for specimens compacted without reheating at the plant was taken into the producer's laboratory and immediately compacted into non-reheats. Plant-compacted specimens were provided to the Virginia Transportation Research Council (VTRC) for testing. The testing on non-reheats included testing for volumetric properties by the producer and the corresponding VDOT district (if available) and VDOT balanced mix design (BMD) tests (i.e., Cantabro test, Asphalt Pavement Analyzer [APA] rut test, and indirect tensile cracking test [IDT-CT]).

Next, loose plant-produced mixtures were placed into boxes, transported to VTRC, and stored in a climate-controlled area until further evaluated. To transform the mixture into reheats, the specimens were then fabricated by reheating the loose mixtures until they became workable, splitting the material into appropriate quantities, heating the material to the compaction temperature and compacting the material. The experimental program included testing: volumetric properties tests, VDOT BMD tests, and short- and long-term aged specimens tests.

The additional testing of short-term aged specimens consisted of the following tests:

- Indirect tensile test at high temperature (IDT-HT).
- Indirect tensile rutting test (IDEAL-RT).
- Dynamic modulus |E*| test.
- Stress sweep rutting (SSR) test.
- Repeated load triaxial (RLT) test.
- Cyclic fatigue (CF) test.

The additional testing also include these tests on loose mixtures that were further aged for 8 hours at 135°C prior to compaction (referred to herein as “reheats-LTOA”). The long-term aged performance was evaluated using the dynamic modulus |E*| test, IDT-CT test, and CF test.

Literature Review

The latest advancements and relevant information pertaining to the objective of this study were consolidated through a comprehensive literature review. This review was conducted by exploring several transportation engineering-related databases and search engines, including the Transport Research International Documentation bibliographic database, the Catalog of Worldwide Libraries, and Google Scholar.

Asphalt Binder Testing and Characterization

Performance Grading

Asphalt binder performance grading was performed in accordance with AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder (AASHTO, 2017), and AASHTO M 332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test (AASHTO, 2019). Testing was performed on virgin asphalt binders and on asphalt binders modified with recycled plastics at various contents in the laboratory during the design stage. Furthermore, testing was performed on asphalt binders extracted and recovered from loose mixtures sampled at the plant during production. Extraction of asphalt binder from collected mixtures was performed in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA), Method A, using n-propyl bromide as the solvent (AASHTO, 2018). The asphalt binder then was recovered from the solvent using the Rotavap recovery procedure specified in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures (AASHTO, 2019).

Difference in Critical Low Temperature Performance Grade (ΔTc)

The calculation of the difference in critical low temperature PG limiting temperatures, ΔT_c, entails subtracting the m-critical low temperature ($T_{c,m}$) from the S-critical low temperature ($T_{c,S}$), as shown in Equation 1 (Federal Highway Administration [FHWA], 2021a).

$$\Delta T_c = T_{c,S} - T_{c,m} \qquad \text{[Eq. 1]}$$

Both temperatures were determined using the bending beam rheometer in accordance with AASHTO T 313, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binders Using the Bending Beam Rheometer (BBR) (AASHTO, 2019). The *m*-critical low temperature ($T_{c,m}$) is the temperature at which the creep relaxation m-value at 60 seconds of loading is exactly equal to the specification value of 0.300. The *S*-critical low temperature ($T_{c,S}$) is the temperature at which the creep stiffness S-value at 60 seconds of loading is exactly equal to the specification value of 300 MPa.

Frequency Sweep

Frequency sweep tests were conducted to evaluate asphalt binders extracted and recovered from loose mixtures sampled at the plant during production over multiple frequencies and temperatures in terms of dynamic shear modulus (G*) and phase angle (δ) master curves. The induced strains were monitored and kept within the linear viscoelastic region. Binder specimens were tested at temperatures of 45°C, 55°C, 65°C, 75°C, and 85°C using a 25-mm-diameter plate with a 1-mm gap. In addition, testing was performed on binder specimens at temperatures of 5°C, 15°C, 25°C, 35°C, and 45°C using an 8-mm-diameter plate with a 2-mm gap. All specimens were evaluated at 16 frequencies ranging from 0.1 to 100 rad/s at each testing temperature. No standard currently exists for the construction of a binder master curve. In this study, the rheological software package Rheology Analysis Software (RHEA) was used to perform the shifting of the G* master curves to a reference temperature of 45°C (Abatech, 2022; Habbouche et al., 2022).

Glover-Rowe Parameter

The Glover-Rowe (G-R) parameter, determined using Equation 2, captures both rheological parameters needed to characterize binder viscoelastic behavior: stiffness (represented by the complex shear dynamic modulus G*) and relaxation (represented by the phase angle δ) (Anderson et al., 2011; Glover et al., 2005; Rowe et al., 2011).

$$G - R = \frac{G^*(cos\delta)^2}{sin\delta} \qquad \text{[Eq. 2]}$$

where—

G^* = complex dynamic shear modulus, Pa
δ = phase angle, °.

In this study, two versions of the G-R parameter, referred to herein as G-R1 and G-R2, were considered. G-R1, determined at a temperature of 15°C and a frequency of 0.005 rad/s, has a strong correlation with ductility, cracking resistance, and binder oxidation levels (Ruan et al., 2003). The G-R2 parameter was determined at a frequency of 10 rad/s and at the corresponding binder fatigue test temperature. The specific test temperature was determined based on the low PG of the binder, as indicated by Christensen and Tran (2022).

Linear Amplitude Sweep (LAS) Test

The LAS test was conducted in accordance with AASHTO TP 101, Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep, to investigate the fatigue damage characterization of the evaluated binders at an intermediate temperature of interest (AASHTO, 2018). The test included a frequency sweep test at 0.1% strain over a range of frequencies from 0.2 to 30 Hz followed by an amplitude sweep oscillatory shear in strain-control mode test at a frequency of 10 Hz over a range of induced strains from 0.1% to 30%. The test was conducted at 23°C, the average of the high and low PG temperatures minus 4°C for the majority of the evaluated binders. This temperature was also selected such that the linear complex shear modulus G* fell within the range of 12–60 MPa at 10 Hz to mitigate any potential edge flow and/or adhesion loss (Safaei and Castorena, 2016). The binder fatigue performance parameter Nf is calculated using Equation 3.

$$N_f = \mathrm{A} * (\Upsilon_{max})^{-B} \qquad \text{[Eq. 3]}$$

where—

N_f = fatigue performance parameter, number of cycles to fatigue failure.
Υ_{max} = maximum expected binder strain for a given pavement structure.
A and B = modeling parameters associated with fatigue resistance of the binder.

Asphalt Mixtures Testing and Characterization

Volumetric Properties and Aggregate Gradations of Mixtures

Mixtures produced in the laboratory were evaluated in terms of volumetrics during the mix design stage. However, in this report, for the sake of brevity, only data related to the volumetrics of plant-produced mixtures, collected during production, were provided. The theoretical maximum specific gravity of each mixture was determined following the guidelines of AASHTO T 209, Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures (AASHTO, 2020). The asphalt binder content of each mixture was determined by the ignition method as Virginia Test Method (VTM) 102, Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method (Virginia Test Methods, 2013a). The size distribution (gradation) of the recovered aggregate was determined in accordance with AASHTO T 11, Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing (AASHTO, 2020), and AASHTO T 27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (AASHTO, 2020). Loose mixtures were conditioned at the compaction temperature and then compacted to N_{design} gyrations using a Superpave gyratory compactor in accordance with AASHTO T 312, Preparing and Determining the Density of Asphalt Mixtures Specimens by Means of the Superpave Gyratory Compactor (AASHTO, 2019). Various physical characteristics and volumetric parameters in terms of bulk specific gravity (G_{mb}), voids in total mixture (VTM), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), fines to aggregate ratio (FA), aggregate bulk specific gravity (G_{sb}), aggregate effective specific gravity (G_{se}), absorbed asphalt binder content (P_{ba}), effective asphalt binder content (P_{be}), and effective film thickness were determined.

Cantabro Mass Loss

The Cantabro mass loss was determined to evaluate the durability of asphalt mixtures in accordance with AASHTO T 401, Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens (AASHTO, 2022). The test was performed on specimens fabricated from loose mixture collected at the plant during production. Three replicates were tested for each mixture, and an average mass loss was reported.

The source of artificially weathered material for microplastics analysis was material abraded from laboratory compacted specimens during the Cantabro mass loss test. Prior to each test run, all testing equipment was thoroughly cleaned to remove dust and debris from prior runs. Upon completion of each run abraded material accumulated in the bottom pan of the Cantabro drum was collected using metallic scoops and utensils and transferred to sealed aluminum cans for storage and further analysis.

Dynamic Modulus |E*|

The dynamic modulus (E*) of specimens compacted from loose mixtures collected during production was determined using the Asphalt Mixture Performance Tester (AMPT) in accordance with AASHTO T 342, Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA) (AASHTO, 2019). Testing was conducted at three different temperatures (4, 20, and 45°C) and multiple testing frequencies (10, 1, 0.1, and 0.01 Hz). Results at each temperature-frequency combination for each mixture type were reported for three replicate specimens.

Rutting Performance Tests

Indirect Tension-High Temperature (IDT-HT) and Ideal-Rutting Tolerance (IDEAL-RT)

The IDT-HT was conducted by applying a constant rate of axial displacement on the diametral plane of a test specimen. The test loading rate was 50 mm per min, and the test temperature was 54.4°C dry conditioned in an environmental chamber. Once the IDT-HT was completed, the indirect tensile strength of specimens was determined. A high strength value indicates a good resistance to rutting (Boz et al., 2023b).

The IDEAL-RT, also known as the rapid rutting test, was conducted in a manner like the IDT-HT except this test used a shear fixture used in lieu of a typical IDT-HT fixture in accordance with ASTM D8360, Standard Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using the Ideal Rutting Test (ASTM, 2022). The rutting potential of asphalt mixtures from the IDEAL-RT is quantified through the rutting tolerance (RT) index (RT_{index}). A high RT index indicates a good resistance to rutting (Boz et al., 2023b).

Asphalt Pavement Analyzer (APA) Rut Test

The APA rut test was performed on specimens prepared from loose mixture collected during construction in accordance with AASHTO T 340, Standard Method of Test for Determining the Rutting Susceptibility of Hot Mix Asphalt (APA) Using the Asphalt Pavement Analyzer (APA) (AASHTO, 2019). After 8,000 cycles were applied at a temperature of 64°C, the deformation of the specimen was measured.

Stress Sweep Rutting (SSR) Test

The SSR test assesses the rutting susceptibility of asphalt mixtures in accordance with AASHTO TP 134, Standard Method of Test for Stress Sweep Rutting (SSR) Test Using Asphalt Mixture Performance Tester (AMPT) (AASHTO, 2021). The low and high temperatures were determined for the project location, using LTPPBind, version 3.1 at the location of interest within the pavement structure. The SSR test results were used to calculate the average permanent strain (in percent) and to produce the rutting strain index (RSI) parameter calculated by the FlexMAT rutting analysis (FHWA, 2021b). A lower RSI indicates relatively more resistance to rutting (FHWA, 2021b).

Repeated Loading Triaxial (RLT) Test—Confined Flow Number

The rutting characteristics of specimens prepared from loose mixture collected during construction were evaluated using the RLT test in accordance with National Cooperative Highway Research Program (NCHRP) Report 719, *Calibration of Rutting Models for Structural and Mix Designs* (Von Quintus et al., 2012). The RLT test was conducted at three different temperatures: 30, 40, and 50°C. The Franken model was used to model the permanent strain-loading cycle relationship numerically (Von Quintus et al., 2012).

Cracking Performance Tests

Indirect Tensile Cracking Test (IDT-CT)

The IDT-CT was conducted at 25°C on specimens prepared from loose mixture collected during construction in accordance with ASTM D8225-19, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature (ASTM, 2019). The cracking tolerance (CT) index was then calculated from the test load-displacement. A higher CT index value indicates a better resistance to cracking.

Texas Overlay Test (OT)

The Texas overlay test was performed only on field cores in accordance with Tex-248-F, *Test Procedure for Overlay Test*, to evaluate the mixtures' resistance to reflective cracking (Texas Department of Transportation, 2019). The typical OT specimens were 150 mm long by 75 mm wide. Although the procedure calls for a thickness of 37.5 mm for laboratory-made specimens, the samples tested in this study had a thickness equal to or lower than 37.5 mm, depending on the cores from which they were trimmed. The OT test was conducted in a controlled displacement mode at a loading rate of 1 cycle per 10 seconds with a maximum displacement of 0.6350 mm at 25 ± 0.5°C. The number of cycles to failure was defined as the number of cycles to reach a 93% drop in initial load, which is measured from the first opening cycle. If a 93% reduction in initial load is not reached within a specified number of cycles (5,000), the test stops automatically.

A power function defined in Equation 4 was used to fit the load reduction curve function of the number of loading cycles to determine the crack propagation rate (CPR) (Garcia et al., 2016). The critical fracture energy (G_c) at the maximum peak load of the first loading cycle was determined using Equation 5. G_c was considered the energy required to initiate cracking.

$$NL = N^{CPR} \quad \text{[Eq. 4]}$$

$$G_c = \frac{W_c}{b*c} \quad \text{[Eq. 5]}$$

where—

NL = normalized crack driving force or load at each loading cycle, kN.
N = number of loading cycles.
CPR = crack propagation rate.
G_c = critical fracture energy, kN-mm^{2}.
W_c = fracture area at the maximum peak load of the first loading cycle.
b = specimen width, mm.
h = specimen height, mm.

Direct Tension Cyclic Fatigue (CF) Test

The direct tension CF test was performed in accordance with AASHTO TP 107, Standard Method of test for Determining the Damage Characteristic Curve and Failure Criterion Using the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test (AASHTO, 2021). The developed damage characteristic curves were used with the viscoelastic material properties (i.e., |E*|) to obtain the fatigue behavior of the asphalt mixtures. To define fatigue performance, a fatigue cracking index parameter, referred to as the apparent damage capacity (S_{app}), is usually used. The calculation of S_{app} was conducted with FlexMAT for Cracking, an Excel-based tool provided by the FHWA (FHWA, 2019). The higher the S_{app} value, the more resistance to cracking.

Evaluation of Field Cores

Field core samples of SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2 were collected during construction. Core locations were randomly stratified along the length and width of the section. The following properties were measured for each core: in-place layer thickness, air voids, permeability in accordance with VTM-120 (Virginia Test Methods, 2000), and resistance to cracking by means of the IDT-CT and the OT.

Mechanistic-Empirical Simulations

To quantify and evaluate the impact of using regular E and RPM mixtures on the overall performance of pavements, laboratory-measured performance metrics and mixture volumetric properties were incorporated into a comprehensive mechanistic analysis framework—the FlexPave. FlexPave is a specialized finite element program designed to predict the performance of asphalt pavement throughout its lifespan, specifically regarding fatigue and rutting.

Four pavement structures were considered in this study: structures (i) and (ii), shown in Figures 5a and 5b, simulate medium and high traffic-level pavement structures in Virginia, respectively. Structure (iii), shown in Figure 5c, simulates a typical low-volume pavement structure in Virginia. Structure (iv), shown in Figure 5d, represents an experimental test section. The purpose of the experimental section is to isolate the impact of properties related to SMs (i.e., SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2) in a specific pavement structure.

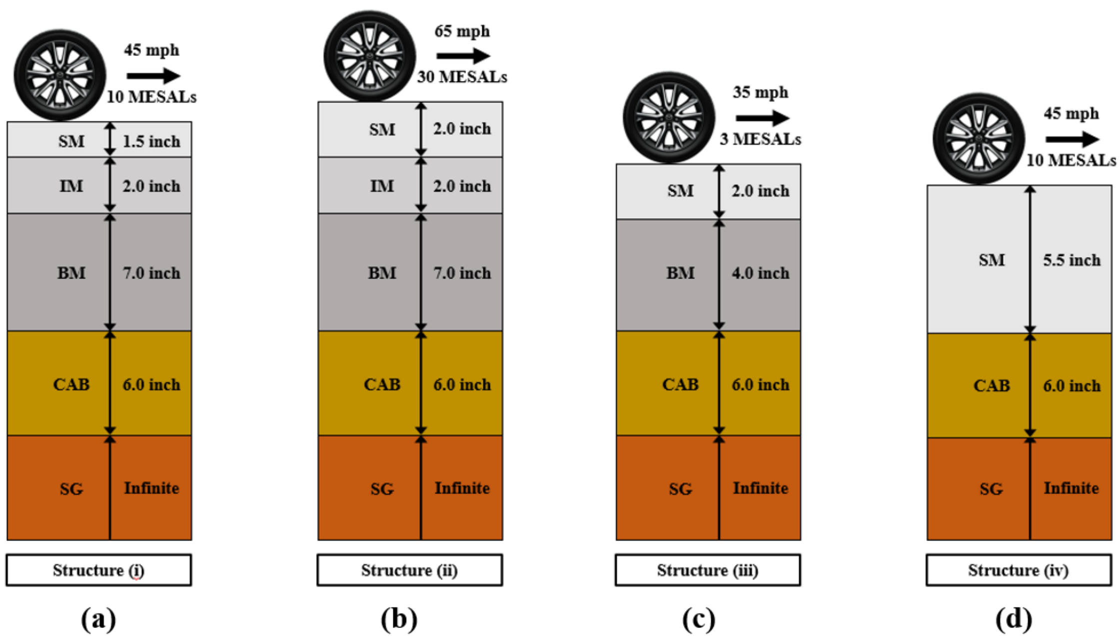


Figure 5. Pavement Structures for Mechanistic-Empirical Simulations: (a) Structure (i); (b) Structure (ii); (c) Structure (iii); (d) Structure (iv). SM = surface mixture; IM = intermediate mixture; BM = base mixture; CAB = crushed aggregate base; SG = subgrade; MESALs = million equivalent single-axle loads.

Non-Destructive Pavement Testing

Ride Quality, Rut Depth, and Mean Profile Depth Testing

The Pavement Design and Evaluation team of the VDOT's Materials Division collected data on ride quality, rut depth, and mean profile depth (MPD), using a VDOT pavement profiler (South Dakota type) in accordance with VTM-106, Determining Pavement Roughness and Rut Depth Using an Accelerometer Established Inertial Profile Referencing System (Virginia Test Methods, 2013b). MPD is a measure of macrotexture that can be calculated from a pavement profile in accordance with ASTM E1845, Standard Practice for Calculating Paving Macrotexture

Mean Profile Depth (ASTM, 2015; Flintsch et al., 2003). High values for the MPD generally indicate a significant percentage of aggregate with a positive texture (Rada et al., 2013).

Falling Weight Deflectometer (FWD) Testing

An independent contractor conducted FWD testing to assess structural capacity in accordance with ASTM D4694, Standard Test Method for Deflections from a Falling-Weight-Type Impulse Load Device (ASTM, 2020). Deflection testing occurred at four load levels (6,000; 9,000; 12,000; and 16,000 lbf) using 250-ft spacing. Following two unrecorded seating drops, four deflection basins were recorded at each load level.

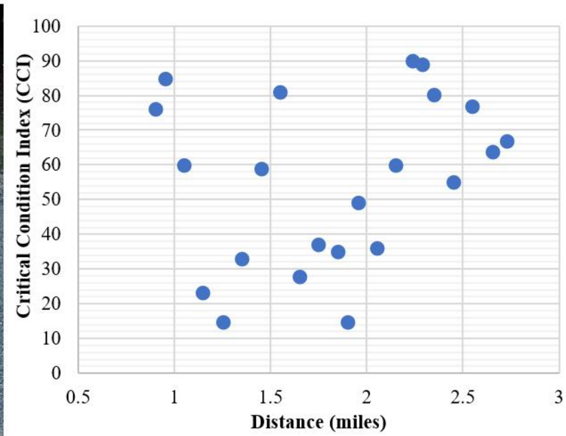
Ground Penetrating Radar (GPR) Testing

An independent contractor also conducted GPR testing using a device with a 2 GHz horn antenna and a vehicle equipped with an electronic distance measuring instrument mounted to the rear wheel that provided synchronous distance data. A GPS unit provided high-resolution, differentially corrected geospatial information as the GPR data was captured. The data collection and recording were controlled by an SIR-30 GPR system operated from within the survey vehicle at a rate of 1 scan per foot of travel. GPR data were processed with RADAN 7 software.

Distress Survey

A visual distress evaluation was conducted before paving. Figure 6a shows the pavement surface on Old Stage Road. The distresses on this section before paving included transverse and longitudinal cracking, localized alligator cracking, rutting, and patching, with no reflective cracking, bleeding, or delamination.

Furthermore, distress data were obtained from VDOT's PMS database for Old Stage Road. The collected distress data covered the period both before (year 2021) and after the recent maintenance cycle (years 2022 and 2023). Within the PMS, VDOT applies three condition indices to assess pavement distresses: (1) the load-related distress rating, (2) the non-load-related distress rating, and (3) the Critical Condition Index (CCI). The load-related distress rating indicates pavement distresses caused by traffic loading; the non-load-related distress rating indicates pavement distresses that are non-load-related, such as those caused by environmental or climatic conditions. These two condition indices are rated on a scale of 0 to 100, where 100 signifies a pavement having no signs of distress. The CCI is the lower of the load-related distress rating and the non-load-related distress rating. In addition to storing the individual distress data, the PMS calculates and stores the load-related distress rating, non-load-related distress rating, CCI, and the International Roughness Index (IRI) for all sections. Further details about the development and implementation of these processes are available in McGhee (2002) and in VDOT (2020). The average CCI prior to paving on the northbound lane of Old Stage Road was 49 (Figure 6b).



(a) **(b)**

Figure 6. Old Stage Road: (a) Photographs of Existing Conditions Prior to Paving; (b) Critical Condition Index of the North Bound Prior to Paving

Microplastic Evaluation: Sample Generation and Preparation

To minimize sample contamination to the greatest extent possible, all sample generation and preparation methods were developed, or existing methods were modified to eliminate or significantly reduce the use of plastic such items as utensils, filters papers, etc. That action meant that the use of glass or metallic storage containers, laboratory utensils, and glass fiber filter papers were needed throughout all stages of sample handling.

Solvent Extraction and Gradation

Abraded material collected during Cantabro testing underwent solvent extraction and centrifugation to remove the binder portion of the asphalt mixture according to AASHTO T 164 (AASHTO, 2018), thereby simplifying the sample matrix for further analysis. Lenium solvent, a mixture of nPropyl-Bromide and isopropyl alcohol, was chosen for its relative safety and efficacy in dissolving bituminous material. However, during compatibility testing, the PET-based P2 recycled plastic additive was readily dissolved by the Lenium solvent. Although other solvents were assessed, they yielded similar results or were ineffective at removing the bituminous material. Alternatively, the HDPE/LDPE-based P1 recycled plastic additive proved highly compatible with the Lenium solvent. It exhibited no appreciable swelling, color change, and, most importantly, weight change (0.38% increase in weight) after exposure to the solvent for 24 hours at room temperature. This exposure time significantly exceeded that used during the extraction process, which typically takes no longer than an hour.

The sample was placed in the aluminum centrifuge bowl, along with enough solvent to fully submerge the material. After completion of solvent extraction, both the binder portion and particulate portion were recovered. The binder portion was collected in a clean aluminum can, and the particulate portion was collected in a glass beaker. After solvent extraction, the recovered particulate portion was sieved into seven particle sizes: ≥2.36 mm, 1.18 mm, 600 µm, 300 µm, 150 µm, 75 µm, and <75 µm. All sieves were thoroughly cleaned beforehand, and each particle size was collected in clean glass beakers, covered with aluminum foil, and stored for further analysis.

Microplastic Evaluation: Testing Procedures and Analysis Approaches

Evaluation and Identification of Suitable Analytical Methods

A variety of analytical methods commonly used to assess traditional forms of microplastics (i.e., those originating from littering, food packaging, etc. found in environmental samples or drinking water) were considered in this research. These methods included hand counting, light and fluorescent microscopy paired with image analysis, scanning electron microscope analysis, gravimetric analysis, and Fourier transform infrared attenuated total reflectance (FTIR-ATR) spectrometry. Although some of these methods provided useful insights into the presence and characteristic morphology of microplastic particles in the sample materials, none of them proved to be reliable in detecting and, more importantly, quantifying microplastic particles in the samples. In contrast to traditional microplastics noted previously, microplastics resulting from this material have undergone a process involving heating and mixing into a complex blend of aggregate and asphalt binder (bitumen), followed by compaction. That process significantly alters the morphology, color, and surface composition of the plastic additives. Figure 7 shows these alterations, which present a scanning electron microscope image of a P1 plastic particle that has been impacted with fine aggregate, reducing the amount of exposed surface available for FTIR-ATR analysis or fluorescent staining methods. Although it is important to note that these tests were conducted, they will not be discussed further in this report for the sake of brevity.

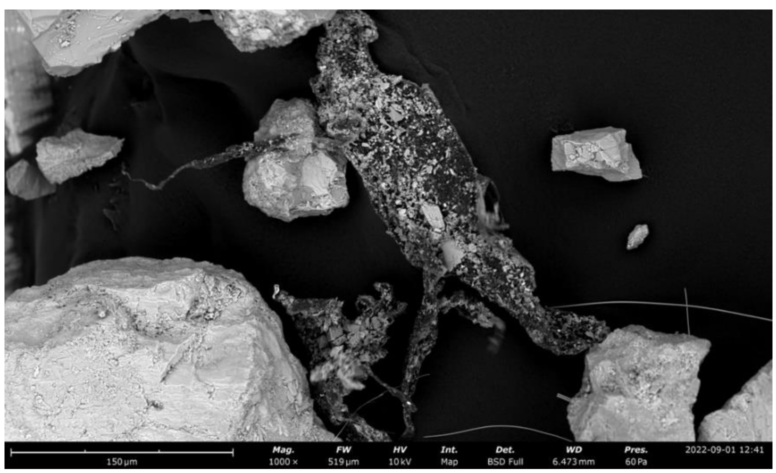


Figure 7. Scanning Electron Microscope Image of Plastic Particle Present in Extracted P1 Sample Material

Ultimately, the analytical method used to generate the results provided in this report consisted of thermogravimetric analysis (TGA) paired with FTIR analysis of the resulting evolved gases. This methodology offers numerous advantages, including a high degree of precision (±0.01% weighing precision), repeatability, and sample throughput in comparison with the other methods evaluated (Mansa, 2021; Nel, 2021; Yu, 2019). However, the methodology does have limitations, particularly concerning the FTIR portion (Mansa, 2021; Nel, 2021; Yu, 2019). At this time, these limitations are mitigated because the types of plastics being added are known, and the asphalt binder portion of the mixture is being extracted. Nevertheless, adaptation of these methods for application to field samples will likely require additional analytical steps, such as mass spectrometry (MS), to identify specific plastic types. It becomes particularly important when attempting to identify the source of microplastics in environmental samples.

For clarity, the layout of the instrumentation used for this analysis is provided in Figure 8. When paired together, the TGA results provide a measure of the concentration of a component through mass loss at a specific characteristic temperature, and the FTIR provides additional verification that the mass loss of the sample was due to the pyrolysis of the component of interest, in this case, microplastics. The following sections provide more specific information related to instrument settings, development of reference libraries, and sample size for the TGA-FTIR analysis.

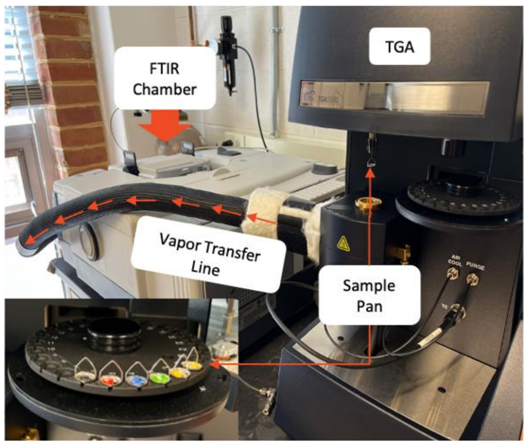


Figure 8. Thermogravimetric Fourier Transform Infrared Analyzer (TGA-FTIR) Instrument Layout

Thermogravimetric Analysis

TGA was conducted on both the P1 and P2 plastic additives received from the manufacturer and the extracted particulate matter and asphalt binder from the P1, P2, and control/reference mixtures. The analysis was performed using a TA Waters TGA 5500 thermogravimetric analyzer with platinum high-temperature sample pans. All tests were carried out under nitrogen at a purge rate of 20 ml/min and involved two heating ramps to reach a maximum temperature of 800°C. The first ramp heated samples to 150°C at a rate of 30°C/min. The second ramp increased the temperature to 800°C and utilized a dynamically changing temperature ramp rate at 15°C/min. This dynamic temperature ramp was designed to capture detailed mass loss data by adjusting (e.g., decreasing) the heating ramp rate during periods of greater mass loss, essentially enabling the instrument to capture more data points during these significant events. Prior to each test run, the TGA-FTIR system was purged with nitrogen at a rate of 40 ml/min for 3 min to clear the system of ambient air and water vapor (to the best extent possible). Additionally, at the end of each sample run, the system was held at the maximum temperature of 800°C for 1 min and again purged with nitrogen at a rate of 40 ml/min to clear the system of any residual sample.

Reference thermograms were developed for both evaluated plastic additives (P1 and P2) along with the virgin binders used in the mixtures. Because P1 was a more heterogeneous material, reference thermograms were collected for the predominant plastic colors, including black, blue, brown, green, orange, red, white, yellow, translucent yellow, and clear. These reference thermograms were used to identify the characteristic temperatures at which the P1 and P2 plastics pyrolyzed for use when quantifying any mass loss associated with microplastics and determining (e.g., timing) when to collect FTIR spectra of evolved gases. Characteristic temperatures, indicating the point of largest mass loss, were calculated from these reference thermograms.

Because of the relatively small sample size limitation of the TGA instrument (maximum of 50 mg per sample), 4–11 thermograms were collected for each particle size of the extracted sample material, referred to as P1-Ext and P2-Ext. The number of replicates was determined by the amount of material available for testing or variability in preliminary mass loss results. All subsamples were randomly pulled from each well mixed sample beaker. Additionally, samples of P1-Ext material from the 1.18 mm and 2.36 mm particle sizes were sorted by hand to isolate suspected microplastic particles prior to testing. This concentration and reduction of sample mass ensured the sample fell below the 50 mg constraint of the TGA instrument.

FTIR Vapor Analysis

Infrared spectra of the evolved gases were collected continuously (as a series) throughout the entire secondary heating ramp, using a Thermo Scientific Nicolet iS50 FTIR spectrometer. All spectra were collected at a resolution of 4 cm^{-1} with 16 scans per interval, and a sampling interval of 23.65 second, covering a spectral range of 400 cm^{-1}– 4000 cm^{-1}. Before analyzing each sample, 64 background scans were collected of the dry nitrogen purge gas flowing through the TGA testing chamber at a rate of 20 ml/min. Additionally, the transfer line and FTIR gas cell were heated to 300°C during testing to prevent vapor deposition during testing.

Reference spectra were collected during each TGA reference run and used to generate a library of known spectrum. Only the spectra collected at the maximum signal intensity, identified based on the Gram-Schmidt profile (as shown at the top of Figure 9), were included in these libraries. These reference spectra underwent no further manipulations except for background subtraction. For each plastic additives, two separate libraries were generated. Specifically, for the P1 library, 10 reference spectra were collected for each of the predominant plastic colors present in the material as previously noted. FTIR spectra were collected for a subset of each particle size of the extracted material using the same instrument settings employed during the development of the reference library. Collected spectra were then compared against the developed reference library and other commercially available reference libraries to identify the possible composition of the evolved gases. This comparison was performed using the search function in Thermo Fisher Scientific's Omnic software. This search function identifies and compares the position of the peaks in an unknown spectrum with those present in each reference spectra. Match values were generated by Omnic based on how well the peak positions in the unknown spectrum overlap with those in a given reference spectrum with 0 equaling no overlap and 100 equaling complete overlap. Generally, a match value greater than 85 indicates a good match to the reference spectrum (Thermo Electric Corporation, 2006).

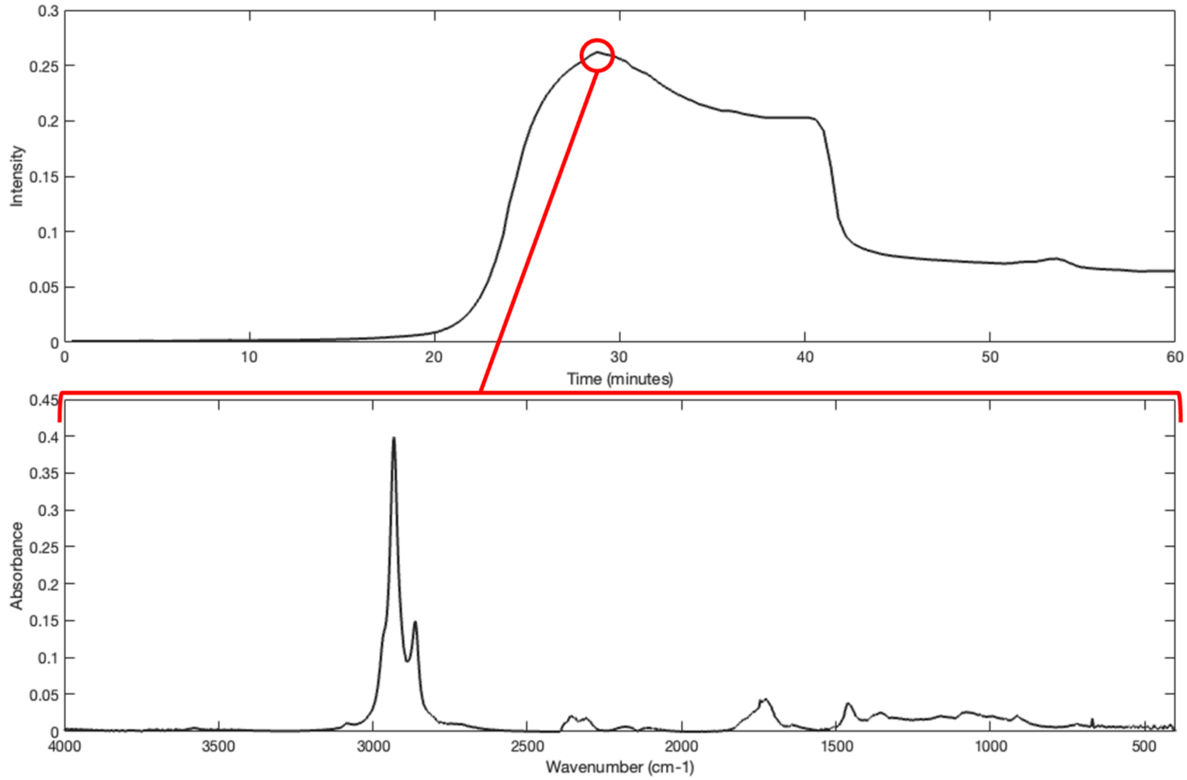


Figure 9. Fourier Transform Infrared Analyzer Spectra Collected from a Sample of Black P1 Additive About 28 Minutes into the TGA Run

Unfortunately, over the course of the testing period, a manufacturing defect in a high-temperature fitting caused a blockage and leakage of the transfer line connecting the TGA furnace to the FTIR detector. As a result, complete FTIR results associated with P2-Ext samples were not collected in time for the preparation of this final report and, therefore, are not included.

RESULTS AND DISCUSSION

Literature Review

Several documents and peer-reviewed papers have been published to evaluate the use of plastics in asphalt mixtures. Including these documents, the research team referred to the following, among many others:

- Willis, R., Yin, F., and Moraes, R. *Recycled Plastics in Asphalt Part A: State of the Knowledge*. NAPA – IS – 142, National Asphalt Pavement Association, Greenbelt, Maryland, 2020.
- Yin, F., Moraes, R., and Anand, A. *Recycled Plastics in Asphalt Part B: Literature Review*. NAPA – IS – 142, National Asphalt Pavement Association, Greenbelt, Maryland, 2020.
- National Center for Asphalt Technology (NCAT), Western Research institute (WRI), Gayle H. King (GHK), and Dow. *NCHRP Project 09-66 – Interim Report:*

Performance Properties of Laboratory Produced recycled Plastic Modified (RPM) Asphalt Binders and Mixtures. Transportation Research Board, Washington, D.C., 2021. https://onlinepubs.trb.org/Onlinepubs/nchrp/docs/NCHRP9-66InterimReportwithAppendixFINAL.pdf.

Although significant effort was made to understand the impacts of recycling plastics in asphalt, more research is required by the asphalt, plastics, and petrochemical industries to advance the infrastructure for low-cost recycling of plastics. The literature review in this report focuses solely on the environmental aspect of the project, specifically on sampling and testing potential microplastics in RPM asphalt mixtures.

The available literature on identifying microplastics generated from RPM asphalt mixture is currently limited. In addition, laboratory methods used for identifying microplastics in samples vary widely. Initial methods typically involve a visual analysis of materials to manually sort and quantify microplastics in samples. These methods rely on morphology and color to identify particles of concern. However, as the research team's understanding of this topic has increased, there is a need to detect smaller sized particles and more thoroughly identify specific plastic types. In response to this, recent research on microplastics has focused on using techniques like micro-FTIR or micro-Raman to analyze discrete particles of materials under the microscope (Rosso, 2022; Schymanski et al., 2017; Werbowski et al., 2021).

For example, Rosso et al. (2022) evaluated samples of stormwater runoff collected from a highway in Italy using micro-FTIR analysis. In the study, samples of stormwater runoff were oleo-extracted, then solvent rinsed and filtered through aluminum oxide filter papers prior to analysis. Since micro-FTIR provides only qualitative results for individual particles (i.e., determining whether a particle is plastic or not), the results of the study were presented as a count of plastic particles per liter. Out of the four rain events the Italian team sampled, microplastics counts ranged from 11,932 particles per liter to 18,966 particles per liter (Rosso et al., 2022). It is worth noting that these counts represent microplastics ranging in size from 5–100 µm, much smaller than the EPA's current 5 mm definition of microplastics. By comparing the FTIR results with reference libraries of known materials, the authors were able to identify the types of plastic present. Utilizing this count and the typical densities of each plastic type, microplastic concentrations were estimated to range from 925.5 ± 2 µg/L to 3486.5 ± 82 µg/L (Rosso et al., 2022). Although these concentrations are only estimates, the results still provide a valuable reference point.

Another recent study by Werbowski et al. (2021) evaluated anthropogenic particles present in the stormwater runoff collected from 12 different urban areas over 3 storm events in San Francisco, California. It should be noted that the term anthropogenic particles is used in this study as a broad term that includes microplastics and what the Werbowski et al. (2021) study referred to as "black rubbery fragments." In this study, researchers used a combination of sieving and density separation to isolate particles of interest, followed by manual sorting based on color, morphology, and number. A subset of each sorting group was then analyzed using either FTIR for particles greater than 500 µm and micro-Raman for smaller particles to identify polymer types. The study's results showed that particle concentrations ranged from 1.1 to 24.6 particles per liter of stormwater collected. Of these, microplastics made up about 12% of all of the particles identified based on morphology, with polyethylene (PE) found to be the most common polymer type. The most prominent particle types found were fibers and rubbery fragments, representing about 85% of all particles collected. It is not clear why the authors grouped these two particle morphologies together; however, they attribute the particles' presence to the degradation of vehicle tires and pavements.

Although the methods used in these studies were able to provide particle counts and identify specific polymer types, they involved significant sample preparation methods, and the analysis was conducted on a particle-by-particle basis. Similar to other microplastic analysis methods that rely on fluorescent microscopy, image analysis, etc., the labor-intensive nature of these methods results in limited sample sizes (Masura et al., 2015; Primpke et al., 2020; Zhou, 2020). To address this and other concerns, TGA used on its own or paired with FTIR and/or MS was proposed as a suitable alternative (Mansa, 2021; Nel, 2020; Yu, 2019).

In essence, TGA analysis involves measuring the mass loss of a sample as it is heated to a set temperature at a controlled rate. Because most materials pyrolyze, or combust, at specific characteristic temperatures, information related to the composition of a complex mixture of component materials can be gained from this data, assuming, of course, that the components of the mixture are known, along with their characteristic temperatures. The data generated from a TGA run is referred to as a thermogram, with temperature depicted on the x-axis and precent weight on the y-axis. Often, the first derivative of this curve is used to visually identify significant mass loss events. At the top of Figure 10 is an example thermogram where a significant mass loss event occurred at about 450°C. This singular mass loss event indicates that only one component was present in the material, and that component had a characteristic temperature of about 450°C. Using this data, the composition of more complex mixtures can be determined, along with the concentration of each component, as long as their characteristic temperatures do not overlap. For mixtures with unknown components, analysis of the gases generated at these characteristic temperatures can be conducted using FTIR and/or MS to better identify its composition. For example, the bottom of Figure 10 depicts the FTIR spectrum collected from the decomposition gases generated at the characteristic temperature. These spectra are then compared with a reference library of known spectra to identify specific compounds.

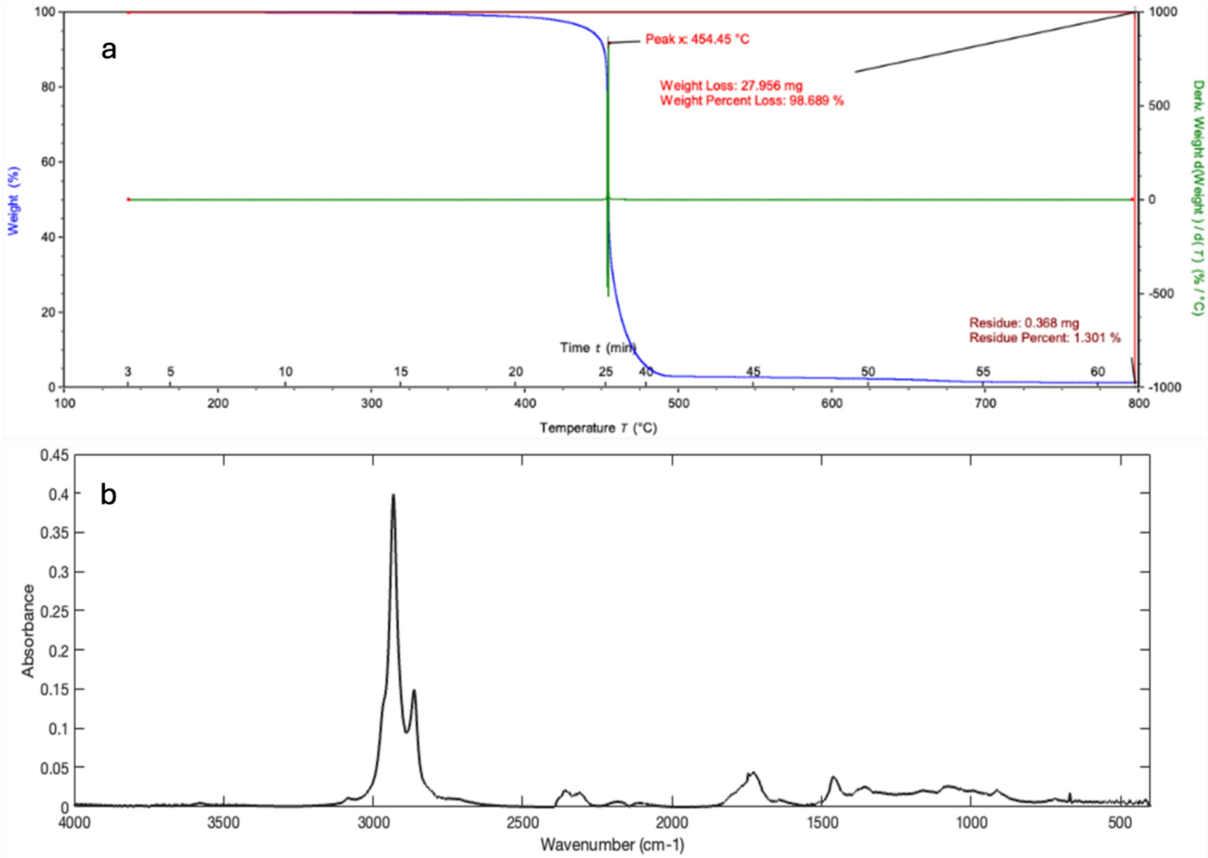


Figure 10. (a) Example Thermogram of Opaque Black P1 Plastic Collected During Development of Reference Thermograms. (b) Infrared Spectrum Collected from the Thermal Event Depicted Above. Note that the spectrum link time is slightly delayed, enabling evolved gases to reach the detector.

Paired TGA-FTIR analysis was conducted by Yu et al. (2019) to identify and quantify microplastics in seawater, soil, and bivalve tissue. That analysis involved testing PE, PET, PP, PS, PVC, and PA plastics on their own (i.e., pure) and spiked into sample materials. TGA results of the pure plastics showed that each type decomposed in a single step, except for PVC, which had two decomposition steps. Table 3 shows the temperature at which decomposition starts and ends and characteristic temperatures (temperature at the maximum mass loss rate) for six types of plastic.

Table 3. Thermogravimetric Results of Various Plastics from Yu et al. (2019)

Plastic Type	Decomposition Start Temperature	Decomposition End Temperature	Characteristic Temperature
PE	430°C	519°C	485°C
PET	430°C	470°C	433°C
PP	390°C	480°C	447°C
PS	375°C	439°C	414°C
PVC	297°C–378˚C (1st step)	420°C–570˚C (2nd step)	330°C (1st step) 460°C (2nd step)
Polyamide (Nylon)	350°C	470°C	458°C

The Yu et al. (2019) analysis found that collecting spectra for the decomposition gases generated at the material's characteristic temperature provided the best signal-to-noise ratio. Using this methodology, the authors found that PP, PE, and PET have similar spectra dominated by peaks at wavenumbers representing ketones (2960 and 2917 cm^{-1}), aromatic/alkanes (1457, 1378, and 890 cm^{-1}), and carbon dioxide (2400 to 2200 cm^{-1}) (Yu et al., 2019). Due to the overlaps both in characteristic temperatures and infrared spectra, the authors were unable to distinguish between these three polymer types when mixed together. Although Yu et al. (2019) did not pursue further method development for these plastics, these results still hold promise for the study addressed in this report, especially since this report used material that contained only one plastic type. That being said, others have conducted further analysis of the evolved gases, using MS, which proved to be effective at differentiating PP, PE, and PET plastics (Mansa, 2021; Nel, 2021).

Laboratory Performance Evaluation of Asphalt Binders

Performance Grading

The virgin asphalt binders and asphalt binders modified with recycled plastics P1 at various contents were evaluated in terms of PG during the design stage in the laboratory. The data summarizing these evaluations can be found in the corresponding supplemental files for this report. The testing specifically focused on asphalt binders modified with recycled plastic P1 because P2 was designed to enhance the performance properties of the corresponding asphalt mixtures with minimal impact on the base binder. Only 4% of P1 by total weight of binder was needed to transform the base binder from a 64S to a 64E binder, where S and E denote standard and extremely heavy traffic, respectively. However, it was observed that an increase in P1 content had a negative effect on the PG low-temperature properties of the base binder. Finally, the E binder exhibited the best performance in terms of binder properties among all evaluated asphalt binders. After conducting tests on the modified binders and mixtures in the laboratory and considering account safety factors, a P1 content of 5% by the total weight of the binder was incorporated into the mixture, resulting in SM-12.5RPM P1. It is crucial to emphasize that the binders modified with recycled plastics underwent a wet process in the laboratory. In contrast, during production, both types of plastics were added through a dry process and subsequently extracted and recovered. This production method could potentially lead to significant differences. One major concern arises from the lower degree of plastic dispersion in the binder during the dry process, as well as the uncertainty about the ability to extract and recover all plastics in the binder. These factors remain unknown and could substantially impact the final binder properties.

Table 4 summarizes the PG and rheological properties of the extracted and recovered binders for the four asphalt mixtures evaluated in this experiment: SM-12.5D, SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2. Two important points need consideration for this analysis:

- SM-12.5D contained 30% RAP, and RAP content was limited to 15% in the remaining mixtures (SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2).
- There was no binder replacement with the addition of P1 to SM-12.5RPM P1, and there was a total binder replacement with the addition of P2 to SM-12.5RPM P2.

Table 4. Performance Grading Results of Extracted and Recovered Asphalt Binders

Property		Test Results: Mixture / Extracted and Recovered Binder ID SM-12.5D	SM-12.5E	SM-12.5RPM P1	SM-12.5RPM P2
As-recovered, Dynamic Shear, 10 rad/s, specification: $\|G^*\|/\sin\delta > 2.2$ kPa					
As-recovered $\|G^*\|/\sin\delta$, kPa	64°C	2.70	--	--	--
	70°C	1.28	--	3.64	4.15
	76°C	--	3.97	1.73	1.94
	82°C	--	2.09	--	--
As-recovered Failure Temperature, °C		**65.7**	**81.2**	**74.1**	**75.0**
PAV20, Dynamic Shear, 10 rad/s, specification: $\|G^*\|.\sin\delta < 5{,}000$ kPa					
PAV20 $\|G^*\|.\sin\delta$, kPa	19°C	--	--	--	--
	22°C	--	6,474	6,065	--
	25°C	6,129	4,684	4,438	5,280
	28°C	4,545	--	--	3,918
PAV20 Failure Temperature, °C		**27.0**	**24.4**	**23.9**	**25.5**
PAV20, Creep Stiffness, 60 sec, specification: Stiffness (S) < 300 MPa and m-value > 0.300					
PAV20 Stiffness (S), MPa	-6°C	127	--	--	--
	-12°C	251	190	182	231
	-18°C	516	381	375	46
PAV20 m-value	-6°C	0.351	--	--	--
	-12°C	0.288	0.312	0.320	0.303
	-18°C	0.243	0.263	0.272	0.251
PAV20 Stiffness Failure Temperature (T_s), °C		-13.5	-15.9	-16.1	-14.2
PAV20 m-value Failure Temperature (T_m), °C		-10.8	-13.4	-14.4	-12.3
PAV20 Low Failure Temperature[a], °C		**-20.8**	**-23.4**	**-24.4**	**-22.3**
PAV20 $\Delta T_c = T_S - T_m$, °C		-2.7	-2.5	-1.7	-1.9
Performance Grade (AASHTO M 320)		**PG 64-16**	**PG 76-22**	**PG 70-22**	**PG 70-22**
RTFO J_{nr} at 64°C, kPa^{-1}	0.1 kPa	0.51	0.18	0.89	0.78
	3.2 kPa	0.56	0.22	1.02	0.87
RTFO Recovery at 64°C, %	0.1 kPa	14.6	57.0	12.2	10.2
	3.2 kPa	9.8	48.3	5.5	5.3
Performance Grade (AASHTO M 322)		**PG 64V-16**	**PG 64E-22**	**PG 64H-22**	**PG 64H-22**
PAV40, Creep Stiffness, 60 sec, specification: Stiffness (S) < 300 MPa and m-value > 0.300					
PAV40 Stiffness (S), MPa	-6°C	147	120	134	135
	-12°C	298	233	244	272
	-18°C	527	427	411	490
PAV40 m-value	- 6°C	0.314	0.319	0.302	0.315
	-12°C	0.274	0.284	0.282	0.278
	-18°C	0.228	0.239	0.242	0.233
PAV40 Stiffness Failure Temperature (T_s), °C		-12.1	-14.5	-14.4	-13.0
PAV40 m-value Failure Temperature (T_m), °C		- 8.0	- 9.1	- 6.6	- 8.3
PAV40 Low Failure Temperature[a], °C		**-18.0**	**-19.1**	**-16.6**	**-18.3**
PAV40 $\Delta T_c = T_S - T_m$, °C		-4.1	- 5.4	- 7.8	- 4.7

SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; P1 and P2 = recycled plastic products; extracted and recovered. [a] Testing temperature is 10°C warmer than the actual low performance grade.

Further details regarding these points are provided in the "Volumetric Properties and Aggregate Gradations" section. SM-12.5D exhibited a PG high temperature of 64°C (65.7°C). Both RPM asphalt mixtures, SM-12.5RPM P1 and SM-12.5RPM P2, showed PG high temperatures of 70°C (74.1°C and 75.0°C, respectively), and SM-12.5E exhibited a PG high temperature of 76°C (81.2°C), in accordance with AASHTO M 320. This suggests that the addition of recycled plastics increased the PG high temperature compared with SM-12.5D mixtures but did not reach the high temperature of SM-12.5E. The four binders showed PG intermediate temperatures ranging between 23.9°C (lowest for SM-12.5RPM P1) and 27.0°C (highest for SM-12.5D). PG low temperatures varied from -24.4°C (lowest for SM-12.5RPM P1) to -20.8°C (highest for SM-12.5D) after 20 hours of aging in the pressure aging vessel (PAV.) This fact suggests that the addition of recycled plastics might improve the PG intermediate and low temperatures when compared with SM-12.5D and SM-12.5E mixtures. However, after 40 hours of aging in the PAV, SM-12.5E and SM-12.5D outperformed RPM asphalt mixtures in terms of low failure temperatures. Finally, a notable decrease in MSCR properties (such as higher non-recoverable creep compliance and lower percent recovery) was observed with the addition of recycled plastics compared with SM12.5E and SM-12.5D.

Table 4 presents the ΔT_c values for all extracted and recovered binders after 20 hours and 40 hours in the PAV. All binders exhibited ΔTc values ranging from -2.7°C to -1.7°C after 20 hours in the PAV and from -7.8°C to -4.1°C after 40 hours in the PAV. None of the binders exceeded the cracking warning limit of -2.5°C after 20 hours in the PAV except for SM-12.5D which was border limit (Diefenderfer et al., 2023; Yang et al., 2022). More positive ΔT_c values were observed with the addition of recycled plastics after 20 hours in the PAV, indicating a promising and comparable resistance of RPM binders with non-load-related cracking. However, similar or more negative ΔT_c values were observed for RPM binders after 40 hours in the PAV. For example, SM-12.5RPM P1 significantly exceeded the traditional cracking zone of -5.0°C after 40 hours in the PAV. Considering whether the existing testing methods are suitable for evaluating RPM asphalt binders, the stability of the recycled plastic polymer should be taken into consideration when subjected to extended aging, in this case, 40 hours in the PAV.

Aging Assessment of Evaluated Asphalt Binders

The G* and δ master curves of the extracted and recovered asphalt binders for the four evaluated mixtures were determined through frequency sweep tests conducted at various testing temperatures and loading frequencies. Three aging conditions were considered: no aging (referred to as As-Recovered) and long-term aging for 20 or 40 hours using a PAV (referred to as PAV20 and PAV40, respectively). Figure 11 displays the G* and δ master curves of the extracted and recovered asphalt binders for SM-12.5D, SM-12.5E, SM-12.5RPM P1, and SM-12.5 RPM P2 after PAV20. The G* and δ master curves for the same evaluated binders at the remaining aging stages are provided in the corresponding supplemental files for this report. All evaluated binders exhibited typical G* master curve shapes, with stiffness (G*) increasing as frequency increased across all considered frequency values (low, intermediate, and high). As Figure 11a shows, SM-12.5D exhibited higher G* values at intermediate and high frequencies compared with the other three mixtures, which displayed similar G*. At low frequencies, SM-12.5E binder showed slightly higher G* values, followed by SM-12.5D, and then both RPM-extracted binders, which exhibited similar G* values.

In Figure 11b, SM-12.5D, SM-12.5RPM P1, and SM-12.5RPM P2 binders displayed typical and similarly shaped δ master curves for unmodified asphalt binders. The phase angle steadily increased as reduced frequency decreased. Meanwhile, SM-12.5E binder exhibited a typical shape of δ master curves for SBS-modified asphalt binders. With decreasing reduced frequency (warmer temperatures), the phase angle values began to increase, reaching a plateau at intermediate reduced frequencies. At this point, the polymer properties surpassed the properties of the base asphalt binder content, causing the phase angle values to increase again at low reduced frequencies.

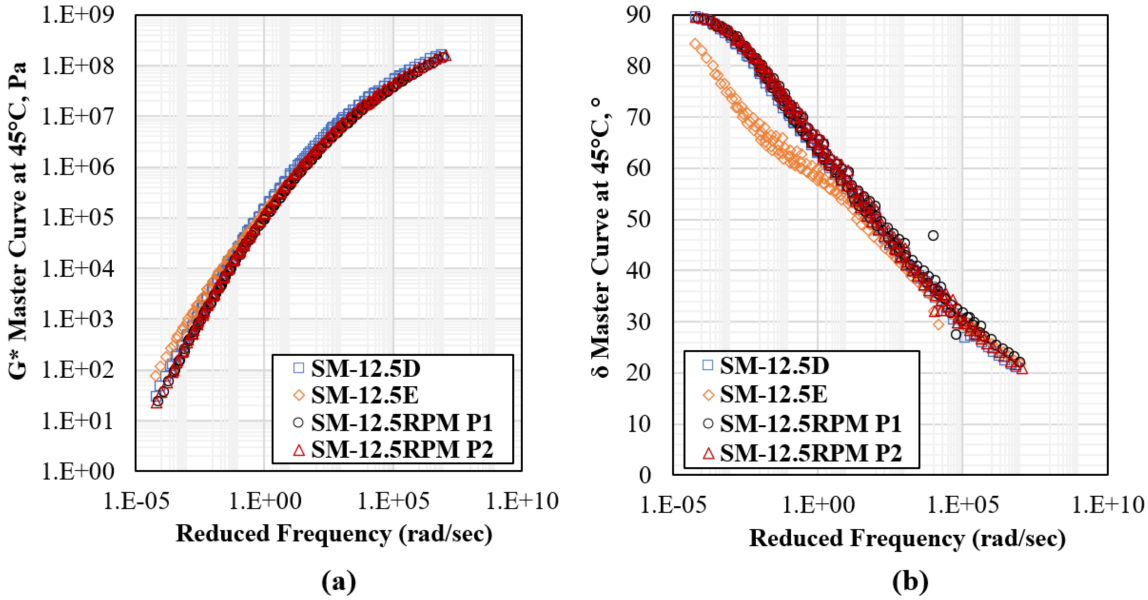


Figure 11. Performance Test Data in Terms of Master Curves at 45°C for All Extracted and Recovered Asphalt Binders at 20-Hour PAV Aging Conditions: (a) Dynamic Shear Modulus (G*); (b) Phase Angle (δ). SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; PAV = pressure aging vessel.

Figure 12a shows the black space diagram constructed by plotting G* versus δ, both determined at 15°C and 0.005 rad/s, as defined for G-R1. The dashed orange line indicates the PG boundaries of G* and δ for RTFO aging conditions (G*/sin δ ≥ 2.2 kPa), whereas the dashed dotted green line represents the PG boundaries of G* and δ for PAV20 aging conditions (Gsin δ ≤ 5000 kPa). Data corresponding to the three aging conditions (As-recovered, PAV20, and PAV40) are shown. Aging led to higher G* and lower δ regardless of the evaluated mixtures, indicating a decrease in resistance to cracking with aging. Generally, a lower G*-δ characteristic suggests lower susceptibility to cracking. SM-12.5D exhibited a higher characteristic compared with SM-12.5RPM P1 and SM-12.5RPM P2, and SM-12.5E had the lowest characteristic. The diagram also illustrates a damage zone where cracking likely begins due to brittle rheological behavior defined by the G-R1 parameter between 180 kPa (the onset of cracking, indicated by the dashed black line) and 600 kPa (significant cracking, indicated by the solid black line). All mixtures exceeded the G-R1 criterion of 180 kPa after 20-hour PAV aging and the G-R1 criterion of 600 kPa after 40-hour PAV aging.

In Figure 12b, another version of the black space diagram is shown, constructed by plotting G* versus δ, both determined at 10 rad/s and the intermediate fatigue temperature as recommended by Christensen and Tran (2022), the conditions defined for G-R2. The dashed orange line indicates the G-R2 threshold of 5,000 kPa. All mixtures exceeded the G-R2 threshold criterion for both PAV20 and PAV40 aging conditions.

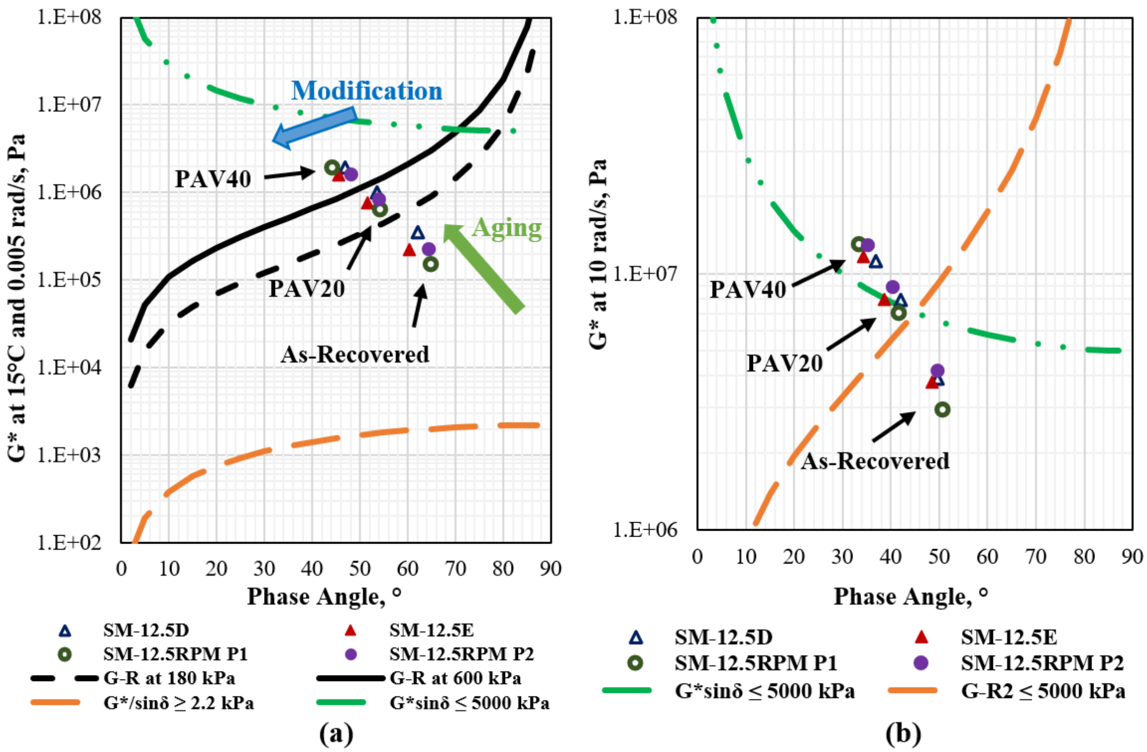


Figure 12. Black Space Diagram in Terms of Dynamic Shear Modulus (G*) and Phase Angle (δ) for All Extracted and Recovered Asphalt Binders at As-Recovered, 20-Hour PAV, and 40-Hour PAV Aging Conditions: (a) G* and δ at 15°C and 0.005 rad/s (G-R1); (b) G* and δ at Intermediate Temperature and 10 rad/s (G-R2). SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; PAV = pressure aging vessel; G-R = Glover-Rowe parameter.

Assessment of Cracking Performance for Evaluated Asphalt Binders

The fatigue life (N_f) of a given asphalt binder can be predicted using the LAS test results coupled with the viscoelastic continuum damage model. Figure 13 shows the fatigue life of the extracted and recovered asphalt binders from D, E, and RPM mixtures after 20-hour and 40-hour PAV aging. The selection of relatively high induced strains (i.e., 5% and 10%) is expected to provide a more reasonable ranking of the evaluated asphalt binders after long-term aging (PAV20 and PAV40). N_f was observed to decrease with the increase in induced strain regardless of the binder/mixture being evaluated, indicating that the LAS is sensitive to strains for D, E, and RPM mixtures. After 20-hour PAV aging, irrespective of the induced strain (i.e., 5% or 10%), SM-12.5D exhibited the lowest N_f, and RPM mixtures exhibited N_f values similar to or higher than those of SM-12.5E, which is higher than SM-12.5D, with SM-12.5RPM P2 having the highest N_f value. However, after 40-hour PAV aging, irrespective of the induced strain, SM-12.5E exhibited the highest N_f, followed by SM-12.5D, and then RPM mixtures, showing the lowest N_f. This result indicates that RPM mixtures may exhibit relatively high resistance to cracking after mid-term aging, but such resistance remains questionable after long-term aging.

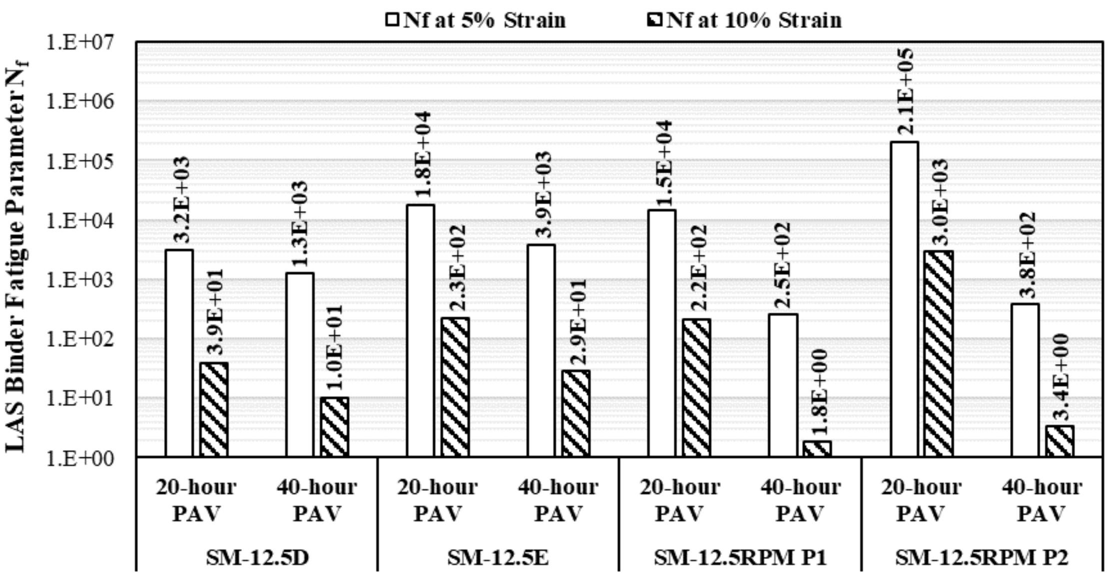


Figure 13. LAS Binder Fatigue Parameter for D, E, and RPM Evaluated Asphalt Binders at the 20-Hour and 40-Hour PAV Aging Conditions at 5% and 10% Induced Strain. LAS = linear amplitude sweep; PAV = pressure aging vessel; SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified.

Laboratory Evaluation of Asphalt Mixtures

Volumetric Properties and Aggregate Gradations of Mixtures

A content of 5% by total weight of binder of P1 was selected for the final mix design based on binder testing, supplemented with verification through corresponding mixture testing. SM-12.5RPM P2 was evaluated only in terms of volumetric properties and performance testing during the mixture design stage at various recycled plastics P2 contents (i.e., 1%, 3%, and 5%). No major impact of P1 content (i.e., 5%) was observed on the volumetric properties. A P2 content of 3% by total weight of binder was selected for optimum durability, cracking, and rutting performance properties. It is important to note that during production, P1 was added to the mixture without replacing any binder, whereas P2 was added as a full binder replacement.

Tables 5 and 6 summarize the volumetric properties and aggregate gradation for the control mixtures (SM-12.5D and SM-12.5E) and RPM mixtures (SM-12.5RPM P1 and SM-12.5RPM P2), respectively, in the mix design and as determined in plant-produced mixtures by the producer, VDOT Richmond district, and VTRC. The VTRC results aligned well with the job-mix formula and the quality control and acceptance data available from the producers and VDOT Richmond district. SM-12.5RPM P1 exhibited a significantly higher total binder content during production when compared with JMF, regardless of the entity conducting the testing (Contractor, VDOT Richmond district, or VTRC). This was expected since plastic P1 was added without replacing any virgin asphalt binder.

Table 5. Volumetric Properties and Gradations for SM-12.5D and SM-12.5E

	Mixture Tolerance/Type								
	Process Tolerance[a]	SM-12.5D				SM-12.5E			
		JMF	Producer	VDOT	VTRC	JMF	Producer	VDOT	VTRC
Composition									
RAP Content, %	-	30				15			
Asphalt Binder ID	-	PG 64S-22				PG 64E-22			
Property									
NMAS, mm	-	12.5				12.5			
Asphalt Content, %	± 0.60	5.80	6.06	6.09	6.10	5.90	6.16	-	6.04
Rice SG (G_{mm})	-	2.508	2.513	2.511	2.504	2.495	2.495	-	2.500
VTM, %	2.0 – 5.0	3.6	2.7	1.8	2.2	3.5	2.6	-	2.4
VMA, %	Min. 15.0	16.0	16.3	15.6	16.0	16.5	16.4	-	15.4
VFA, %	68.0 – 84.0	78	83	88	86.0	79	84	-	84.3
FA Ratio	0.7 – 1.3	1.1	1.1	1.1	1.1	1.1	1.1	-	1.2
Mixture Bulk SG (G_{mb})	-	-	2.445	2.466	2.448	-	2.429	-	2.439
Aggregate Effective SG (G_{se})	-	-	2.770	2.769	2.761	-	2.752	-	2.752
Aggregate Bulk SG (G_{sb})	-	-	2.745	2.744	2.736	-	2.727	-	2.708
Absorbed Asphalt Content (P_{ba}), %	-	-	0.34	0.34	0.34	-	0.34	-	0.61
Effective Asphalt Content (P_{be}), %	-	-	5.74	5.77	5.78	-	5.84	-	5.47
Effective Film Thicness (F_{be}), µm	-	-	-	-	10.1	-	-	-	9.2
Gradation, Percent Passing									
¾ in (19.0 mm)	8.0	100.0	100.0	100.0	100.0	100.0	100.0	-	100.0
½ in (12.5 mm)	8.0	97.0	97.0	97.0	97.8	97.0	97.0	-	95.0
3/8 in (9.5 mm)	8.0	89.0	87.0	87.0	88.6	90.0	87.0	-	86.3
No. 4 (4.75 mm)	8.0	58.0	55.0	54.0	55.3	64.0	63.0	-	61.7
No. 8 (2.36 mm)	8.0	37.0	35.0	36.0	36.2	41.0	41.0	-	41.2
No. 16 (1.18 mm)	-	-	25.0	25.0	25.7	-	28.0	-	28.2
No. 30 (600 µm)	6.0	19.0	18.0	18.0	18.5	19.0	19.0	-	19.5
No. 50 (300 µm)	5.0	-	13.0	13.0	13.2	-	13.0	-	13.6
No. 100 (150 µm)	-	-	9.0	9.0	9.3	-	9.0	-	9.4
No. 200 (75 µm)	2.0	6.1	6.1	6.1	6.5	5.9	6.2	-	6.6

SM = surface mixture; D = mixture deisgnation; E = extremly heavy traffic; JMF = job-mix formula; VDOT = Virginia Department of Transportation; VTRC = Virginia Transportation Research Council; RAP = reclaimed asphal pavement; PG = performance grade; S = standrad traffic; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in miniral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; - = not available.
[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

Table 6. Volumetric Properties and Gradations for SM-12.5RPM P1 and SM-12.5RPM P2

	Mixture Tolerance / Type

	Process Tolerance[a]	SM-12.5RPM P1 (5% by total weight of binder)				SM-12.5RPM P2 (3% by total weight of binder)			
		JMF	**Producer**	**VDOT**	**VTRC**	**JMF**	**Producer**	**VDOT**	**VTRC**
Composition									
RAP Content, %	-	15				15			
Asphalt Binder ID	-	PG 64S-22				PG 64S-22			
Property									
NMAS, mm	-	12.5				12.5			
Asphalt Content, %	± 0.60	5.90	6.95	7.11	6.83	5.90	6.39	6.18	6.06
Rice SG (G_{mm})	-	2.510	2.459	2.460	2.463	2.508	2.502	2.504	2.506
VTM, %	2.0 – 5.0	3.5	2.2	2.0	1.9	3.5	2.5	2.4	2.5
VMA, %	Min. 15.0	16.5	17.1	17.3	16.6	16.5	16.4	15.8	15.6
VFA, %	68.0 – 84.0	79.0	87.0	88.0	88.4	79	85	85	83.9
FA Ratio	0.7 – 1.3	1.1	0.9	0.9	1.0	1.1	1.2	1.1	1.3
Mixture Bulk SG (G_{mb})	-	-	2.406	2.412	2.415	-	2.440	2.444	2.442
Aggregate Effective SG (G_{se})	-	-	2.743	2.753	2.742	-	2.772	2.765	2.761
Aggregate Bulk SG (G_{sb})	-	-	2.699	2.709	2.698	-	2.731	2.724	2.720
Absorbed Asphalt Content (P_{ba}), %	-	-	0.61	0.61	0.61	-	0.56	0.56	0.56
Effective Asphalt Content (P_{be}), %	-	-	6.38	6.54	6.26	-	5.87	5.65	5.53
Effective Film Thicness (F_{be}), µm	-	-	-	-	11.7	-	-	-	8.8
Gradation, percent passing									
¾ in (19.0 mm)	8.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	8.0	97.0	97.0	99.0	96.8	97.0	97.0	98.0	96.7
3/8 in (9.5 mm)	8.0	90.0	91.0	93.0	89.1	90.0	90.0	89.0	88.0
No. 4 (4.75 mm)	8.0	60.0	55.0	56.0	53.5	60.0	65.0	64.0	63.3
No. 8 (2.36 mm)	8.0	40.0	34.0	35.0	33.2	40.0	44.0	44.0	42.8
No. 16 (1.18 mm)	-	-	23.0	24.0	23.4	-	30.0	29.0	29.9
No. 30 (600 µm)	6.0	20.0	17.0	17.0	16.7	20.0	21.0	21.0	20.9
No. 50 (300 µm)	5.0	-	12.0	12.0	12.1	-	15.0	14.0	14.7
No. 100 (150 µm)	-	-	8.0	8.0	8.7	-	10.0	9.0	10.1
No. 200 (75 µm)	2.0	5.9	5.8	5.7	6.1	5.9	7.1	6.4	6.9

SM = surface mixture; RPM = recycled plastic modified; JMF = job-mix formula; VDOT = Virginia Department of Transportation; VTRC = Virginia Transportation Research Council; RAP = reclaimed asphal pavement; PG = performance grade; S = standrad traffic; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in miniral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; - = not available.
[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

Consequently, this resulted in a lower VTM and much higher VFA. For SM-12.5RPM P2, the binder content determined by VTRC was the closest to JMF, followed by VDOT Richmond district and then the producer. No major changes were observed since the contribution of P2 was deducted from the virgin asphalt binder (full binder replacement for the portion of P2). In cases of full binder replacement, the addition of recycled plastics did not seem to affect the volumetric properties when compared with those of D mixtures.

Durability Assessment of Mixtures

Figure 14 shows the Cantabro mass loss of the Design, Non-Reheats, and Reheats specimens for the four evaluated mixtures. Reheats-LTOA specimens were not compacted and tested; therefore, no data is available. For the Design specimens, there was no data for SM-12.5D; however, SM-12.5E exhibited mass loss lower than SM-12.5RPM P1 and higher than SM-12.5RPM P2. For Non-Reheats specimens, RPM mixtures exhibited mass loss values lower than that of SM-12.5D but higher than that of SM-12.5E. For Reheats specimens, SM-12.5RPM P2 had a similar mass loss as SM-12.5D, and SM-12.5RPM P1 had slightly lower mass loss than SM-12.5E, both significantly lower than SM-12.5D. The dashed purple line in Figure 14 refers to VDOT's BMD criterion of 7.5% for Cantabro mass loss of reheats specimens (Diefenderfer et al., 2021).

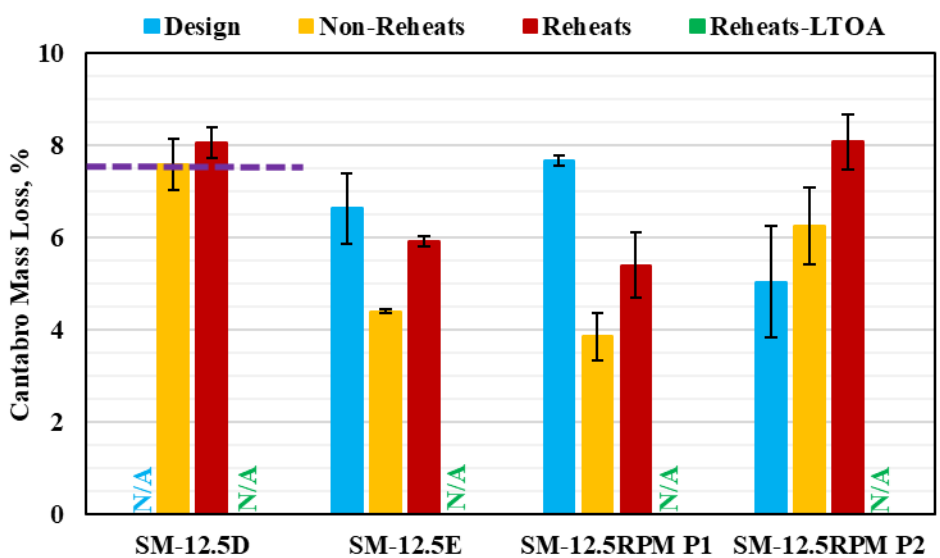


Figure 14. Performance Test Data for Cantabro Mass Loss of D, E, and RPM Mixtures. I-bars indicate mass loss variability ± 1 standard deviation. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; LTOA = long-term oven aged. Dashed purple line = VDOT's balanced mix design limit for D surface mixtures.

Reheats specimens of SM-12.5D and SM-12.5RPM P2 and design SM-12.5RPM P1 did not meet this requirement. However, it is important to mention that these thresholds are applicable solely to D mixtures and are presented here for reference purposes only. Currently, VDOT does not specify a pass/fail criterion for the Cantabro mass loss of SBS-modified and/or RPM mixtures. Overall, the addition of recycled plastics did not jeopardize the durability of asphalt mixtures. Moreover, the type of recycled plastic employed and the mode of binder replacement targeted (no vs. partial vs. full replacement) seem to have a significant impact on the durability of the corresponding mixtures.

Mechanical Property of Mixtures

Figures 15a and 15b show the dynamic modulus |E*| master curves at a reference temperature of 21.1°C for the four evaluated mixtures at short- and long-term aging stages, respectively. Based on the data presented in Figure 15a, a difference in |E*| between SM-12.5D and SM-12.5E was observed, which could be attributed to the SBS elastomeric-modified binder. At higher frequencies and colder temperatures, SM-12.5E exhibited lower |E*| (softer) compared with SM-12.5D. SM-12.5RPM P1, with a higher total binder content (6.83%), demonstrated similar |E*| to SM-12.5E but lower |E*| (softer) compared with SM-12.5D. SM-12.5RPM P2 performed similarly to SM-12.5D at low temperatures and SM-12.5E at high temperatures. After LTOA, more similarities in |E*| were observed among the four evaluated mixtures: at intermediate and high frequencies, SM-12.5D was similar to SM-12.5RPM P1, and SM-12.5E was similar to SM-12.5RPM P2. Additionally, SM-12.5D, SM-12.5E, and SM-12.5P2 exhibited similar |E*| values, which were higher than the ones of SM-12.5RPM P1.

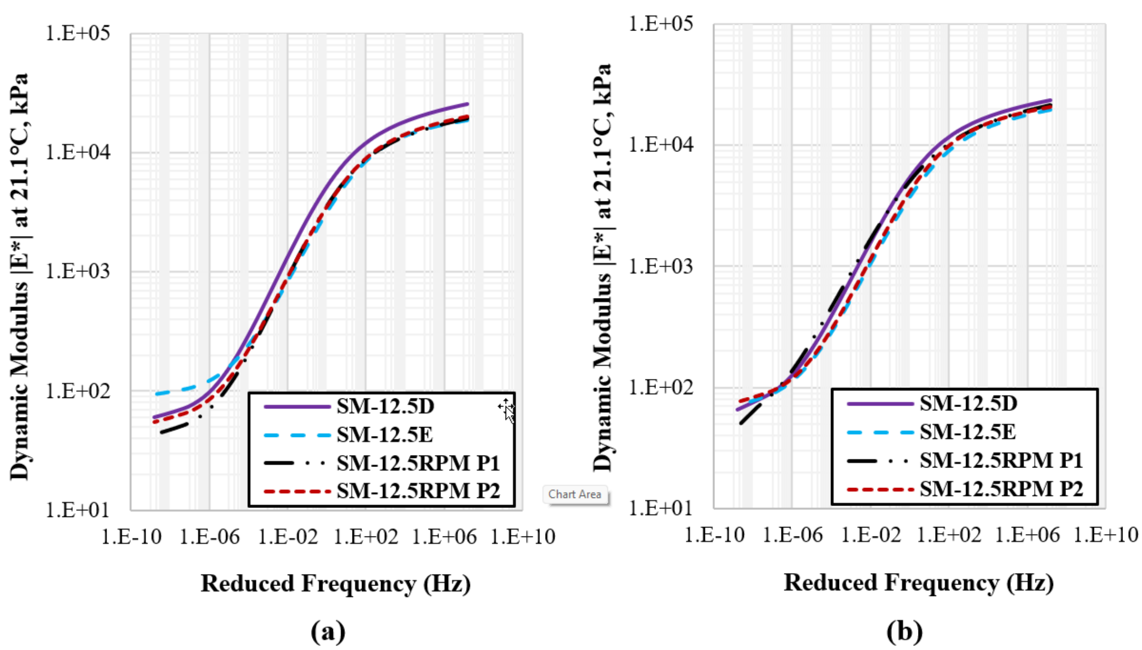


Figure 15. Dynamic Modulus |E*| Master Curves for D, E, and RPM Mixtures: (a) Short-Term Oven Aged; (b) Long-Term Oven Aged. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified.

Figures 16a and 16b show the phase angle (δ) master curves at a reference temperature of 21.1°C for the four evaluated mixtures at STOA and LTOA stages, respectively. The data in Figure 16a revealed that under STOA conditions, SM-12.5D exhibited the highest δ, indicating less elastic behavior, likely due to its relatively high RAP content (30%). SM-12.5RPM P1 showed a similar δ to SM-12.5D, attributable to the plastic P1 polymers added to the mixtures. SM-12.5RPM P2 displayed slightly lower δ compared with SM-12.5D and SM-12.5RPM P1. However, SM-12.5E had the lowest δ, peaking at a relatively higher frequency, owing to the use of the SBS-elastomeric-modified asphalt binder. Similar observations were seen for SM-12.5D, SM-12.5E, and SM-12.5E under LTOA conditions. However, SM-12.5RPM P2 exhibited higher δ values at lower and intermediate frequencies and lower δ values at higher frequencies compared with the other mixtures.

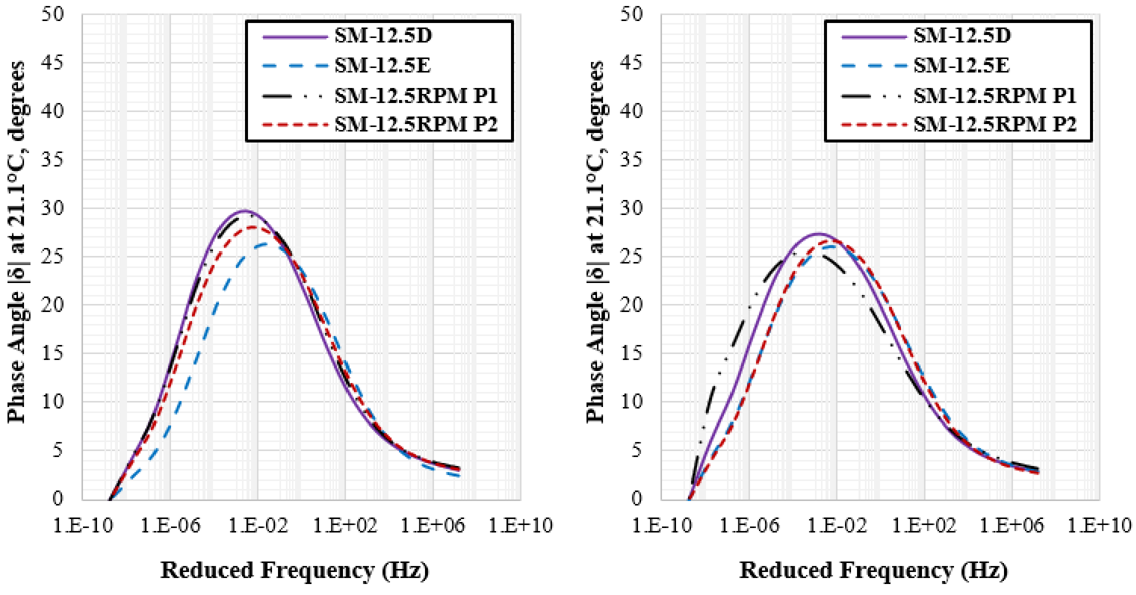


Figure 16. Phase Angle (δ) Master Curves for D, E, and RPM Mixtures: (a) Short-Term Aged; (b) Long-Term Oven Aged. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified.

Assessment of Rutting Performance for Evaluated Mixtures

Five performance tests, pertaining to three levels of complexity (basic, intermediate, and advanced), were conducted to assess the resistance to rutting of the four evaluated mixtures. The basic level included the IDT-HT and IDEAL-RT. The intermediate level included the APA rut test. The advanced level included the SSR and RLT tests. The complexity of performance tests was defined based on the time required for specimen preparation and testing, supplemented by data analysis.

IDT-HT and IDEAL-RT Results and Analyses

The IDT-HT and IDEAL-RT tests were exclusively conducted on Reheat specimens. Figures 17a and 17b show the S_t and RT index values for the four evaluated mixtures. The mean S_t values for these mixtures ranged from 182.0 to 246.7 kPa, with a coefficient of variation (COV) ranging from 4.6% to 13.0% (Figure 17a). Correspondingly, the mean RT index values for the mixtures ranged from 75.5 to 89.3 kPa, with a COV ranging from 9.2% to 19.9%. Overall, the RT index exhibited better repeatability when compared with S_t. Furthermore, the values of S_t and RT index were in complete agreement. Statistical analysis indicated that the four mixtures displayed statistically similar S_t and RT index values. However, in terms of average values, SM-12.5RPM P2 exhibited the highest resistance to rutting (as evidenced by the highest S_t and RT index values), followed by SM-12.5E, then SM-12.5D, and SM-12.5RPM P1. In

Figures 17a and 17b, the dashed purple line indicates VDOT's BMD criteria of 133 kPa and 72 for the IDT-HT S_t and RT index (Boz et al., 2023b). All evaluated mixtures yielded test results surpassing these recommended thresholds. However, it is important to mention that these thresholds are applicable solely to D mixtures and are presented here for reference purposes only. Currently, VDOT does not specify a pass/fail criterion for the IDT-HT S_t and RT index of SBS-modified and/or RPM mixtures.

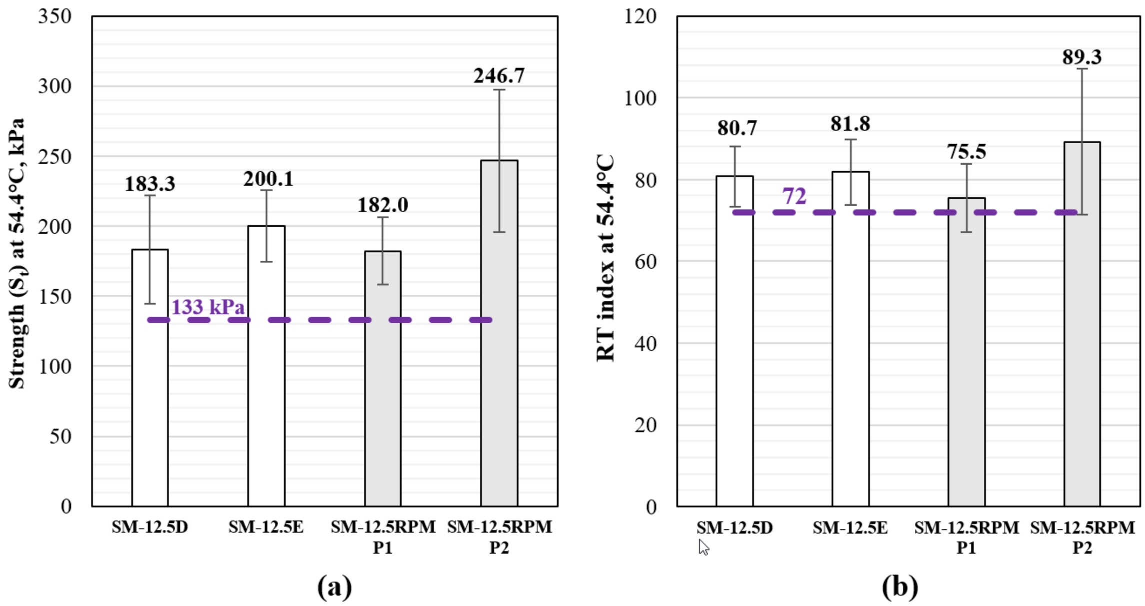


Figure 17. Performance Test Data of D, E, and RPM Mixtures: (a) IDT-HT; (b) IDEAL-RT
I-bars = parameter variability ± 1 standard deviation. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; IDT-HT = indirect tensile test at high temperature; IDEAL-RT = indirect tensile rutting test; RT = rutting tolerance. Dashed purple line = VDOT's balanced mix design limit for D asphalt mixtures.

APA Rut Test Results and Analyses

Figure 18 displays the APA rut depth of the Design, Non-Reheats, and Reheats specimens for the four evaluated mixtures at 64°C after being subjected to 8,000 loading cycles. During the mix design stage, the RPM mixtures exhibited a low APA rut depth (<4.0 mm). In the case of Non-Reheats specimens, all four mixtures showed similar APA rut depths ranging between 4.35 and 5.11 mm, comparable with the rut depth measured on the Design specimens (for those with available data). For Reheats specimens, SM-12.5D exhibited the highest APA rut depth. However, both SM-12.5RPM P1 and SM-12.5RPM P2 exhibited rut depths lower than that of SM-12.5E. This result suggests that the addition of recycled plastic enhances the rutting resistance of corresponding asphalt mixtures, even when replacing the target virgin binder with recycled plastics. The dashed purple line in Figure 18 represents VDOT's BMD criterion of 8.0 mm for the APA rut depth at 64°C after 8,000 loading cycles (Diefenderfer et al., 2021). Of importance is that this threshold applies specifically to D mixtures and is provided here for reference purposes only. Currently, VDOT does not specify a pass/fail criterion for APA rut tests on SBS-modified and/or RPM mixtures conducted in accordance with AASHTO T 340. All evaluated mixtures in this study produced test results lower than the recommended threshold.

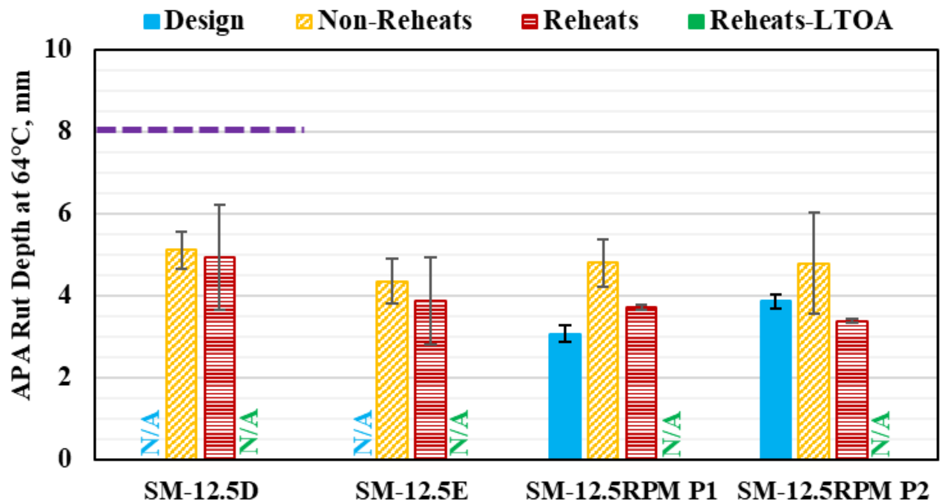


Figure 18. Performance Test Data for APA Rut Depth of D, E, and RPM Mixtures. I-bars indicate rut depth variability ± 1 standard deviation. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; LTOA = long-term oven aged; APA = Asphalt Pavement Analyzer; N/A = not available. Dashed purple line = VDOT's balanced mix design limit for D surface mixtures.

SSR Test Results and Analyses

Figure 19a displays the RSI values for the four mixtures. SM-12.5RPM P1 exhibited the highest resistance to rutting, followed by SM-12.5E, and then SM-12.5D and SM-12.5RPM P2, which showed similar RSI values. This graph indicates that the addition of recycled plastics provides similar or better resistance to rutting when compared with control/reference D and E mixtures. All evaluated mixtures exhibited RSI values above 4%, the recommended threshold for the standard traffic category (3 to 10 million ESALs) (FHWA, 2021b). Note that these traffic categories and their corresponding thresholds may not be directly applicable to these four evaluated mixtures; they are provided here for reference purposes only. The mixtures used to develop these thresholds did not include mixtures from Virginia and/or RPM mixtures.

RLT Test Results and Analyses

Figure 19b shows the rutting relationship at 50°C for all evaluated D, E, and RPM mixtures. The rutting relationships at the three testing temperatures for all evaluated mixtures are detailed in the corresponding supplemental files for this report. SM-12.5D exhibited a significantly higher rutting characteristic than the other three mixtures, irrespective of the number of loading cycles. A lower rutting characteristic signifies a reduced accumulation of permanent strain under loading, indicating better resistance to rutting. Moreover, a flatter curve denotes a lower susceptibility of asphalt mixtures to rutting due to repeated loading. SM-12.5E and SM-12.5RPM P2 exhibited similar rutting relationships, both flatter than those of SM-12.5D and SM-12.5RPM P1. Overall, the addition of recycled plastics enhanced rutting resistance as compared with D mixtures by either reducing the accumulated permanent strains or decreasing the sensitivity of the mixtures to rutting under repeated loading.

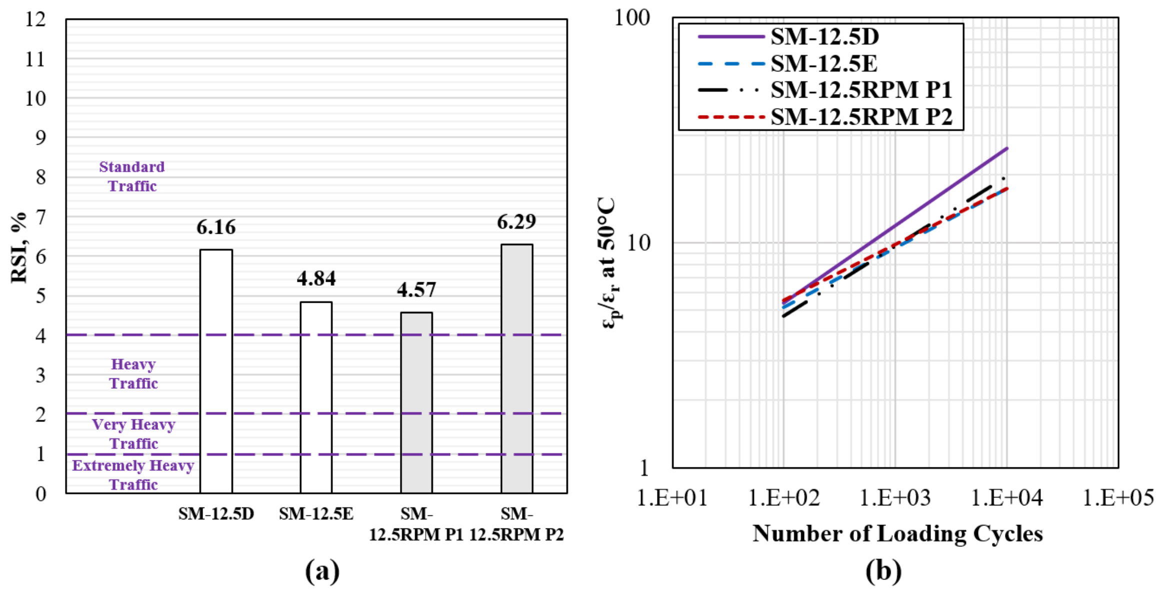


Figure 19. Performance Test Data of D, E, and RPM Mixtures: (a) IDT-HT; (b) IDEAL-RT. I-bars indicate parameter variability ± 1 standard deviation. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; IDT-HT = indirect tensile test at high temperature; IDEAL-RT = indirect tensile rutting test; RT = rutting tolerance. Dashed purple line = VDOT's balanced mix design limit for D asphalt mixtures. Dashed purple lines in Figure 19a = recommended threshold values for the RAI index parameter as a function of traffic tier (FHWA, 2021b).

Assessment of Cracking Performance for Evaluated Mixtures

The IDT-CT (basic level) and the direct tension cyclic fatigue test (advanced level) were performed to assess the resistance to cracking of the four evaluated mixtures.

IDT-CT Results and Analyses

The IDT-CT was conducted in the laboratory on four types of specimens fabricated during the design phase (Design) or from mixtures (Non-Reheats, Reheats, and Reheats-LTOA) collected at the plant. Figure 20 shows the CT index at 25°C for all types of specimens across the evaluated mixtures. The dashed purple line in Figure 20 represents VDOT's BMD criterion of 70 for the CT index at 25°C (Diefenderfer et al., 2021). Note that this threshold specifically applies to D mixtures and is included here for reference purposes only. VDOT does not currently specify a pass/fail criterion for the CT index of SBS-modified and RPM mixtures subjected to heavy traffic. During the design stage, one of the critical factors considered for selecting recycled plastic content was to ensure that the minimum CT index value measured is around the 70 threshold. RPM mixtures exhibited similar or higher CT index values compared with control/reference mixtures, regardless of the specimen type (Non-Reheats, Reheats, and Reheats-LTOA). The CT index decreased with increased reheating and aging across all evaluated mixtures, indicating, as expected, that reheating and aging decrease the resistance to cracking by making the mixture more brittle. Based on the IDT-CT results, one theory is that the addition of recycled plastic does not compromise the cracking resistance of corresponding asphalt mixtures and may even improve that of SM-12.5D. However, there is an ongoing debate regarding the ability of IDT-CT to accurately capture the impact of polymer modification (in this case, SBS and/or recycled plastics) on the cracking performance of asphalt mixtures. This topic was beyond the scope of this project and was not evaluated in this study.

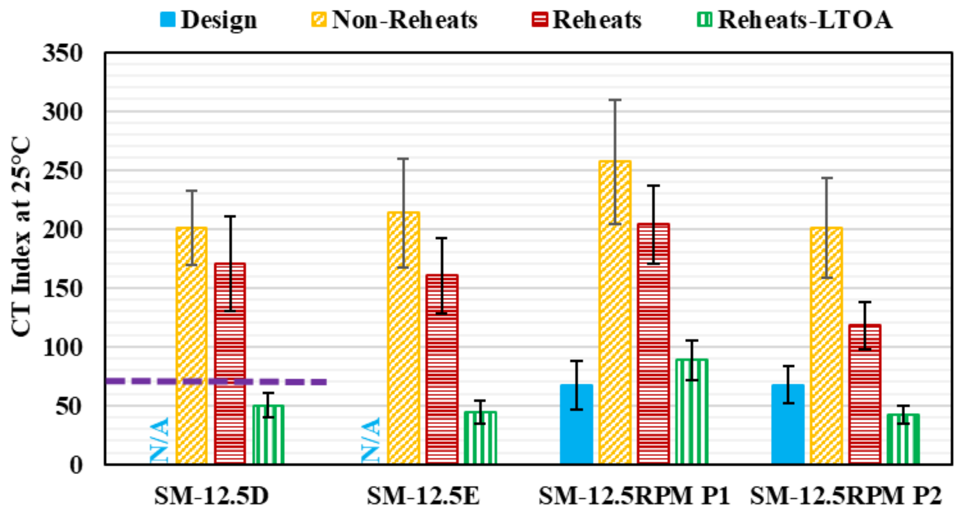


Figure 20. Performance Test Data for IDT-CT of D, E, and RPM Mixtures. I-bars indicate CT index variability ± 1 standard deviation. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; LTOA = long-term oven aged; IDT-CT = indirect tensile cracking test; CT = cracking tolerance. Dashed purple line = VDOT's balanced mix design limit for D surface mixtures.

Figure 21 shows the CT index interaction diagram for D, E, and RPM mixtures in Non-Reheats, Reheats, and Reheats LTOA specimens. This diagram was constructed to provide a better understanding of the effect of polymer modification (using SBS vs. recycled plastics) on the CT index concerning the reference mixture. As shown, the work of fracture values decreases with reheating and/or aging, regardless of the evaluated mixtures. For Design and Reheats specimens, SM-12.5D and SM-12.5E exhibited similar work of fracture values, whereas RPM mixtures showed lower values, regardless of the type of plastics used. In Reheats LTOA, all modified mixtures displayed lower work of fracture when compared with SM-12.5D. SM-12.5RPM P1 exhibited significantly lower l_{75}/m_{75} values than SM-12.5D and SM-12.5E, regardless of the reheating and/or aging stages. Meanwhile, SM-12.5RPM P2 had lower, higher, and similar l_{75}/m_{75} values when compared with SM-12.5D and SM-12.5E in Non-Reheat, Reheats and Reheats LTOA specimens, respectively. The significant difference in binder content results from considering none- to full-binder replacement when adding P1 and P2, respectively. This difference makes it challenging to determine whether the addition of recycled plastics primarily affects the toughness or ductility of the recycled asphalt mixture and to what extent.

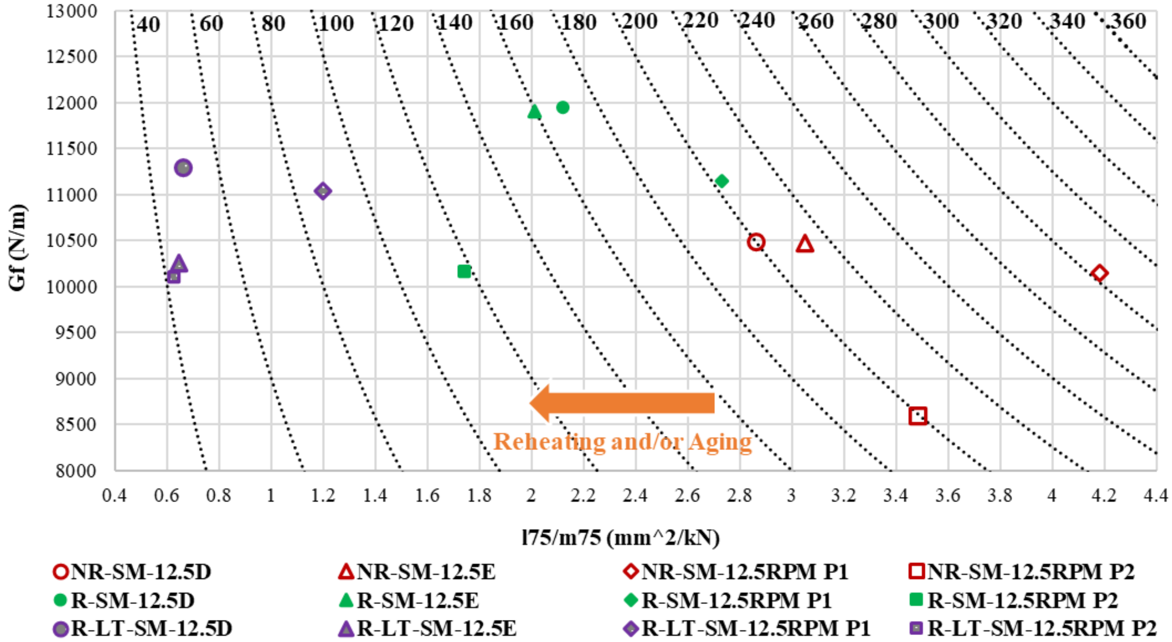


Figure 21. IDT-CT Interaction Diagram for D, E, and RPM Mixtures. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; NR- Non-Reheats; R= Reheats; LT = long-term oven aged; IDT-CT = indirect tensile cracking test; CT = cracking tolerance. The black dotted curves represent various combinations of G_f and l_{75}/m_{75} that lead to a given CT index value.

Direct Tension Cyclic Fatigue Test Results and Analyses

Figure 22a shows the S_{app} values for all D, E, and RPM mixtures at both aging stages (STOA and LTOA). Under STOA conditions, SM-12.5E and SM-12.5D mixtures exhibited the highest and lowest S_{app} values among all evaluated mixtures. The high S_{app} value for SM-12.5E can be attributed to the elasticity induced by the use of SBS polymers. SM-12.5RPM P1 and SM-12.5RPM P2 exhibited S_{app} values that fell between those of SM-12.5RPM D and SM-12.5RPM E, indicating a similar or improved resistance to cracking with the addition of recycled plastics compared with D mixtures. For LTOA conditions, the S_{app} value decreased with aging (LTOA vs. STOA) for all mixtures except for SM-12.5D. Aging did not seem to impact the resistance to cracking of the SM-12.5D mixture, possibly due to its higher RAP content (30%) compared with other mixtures, which may have made the resultant mixtures already aged enough. After aging, SM-12.5E still exhibited the highest S_{app} value, with RPM mixtures showing aged S_{app} values similar to SM-12.5D and falling between SM-12.5D and SM-12.5E.

Stiffness is not the only factor to consider when assessing the fatigue life of mixtures. Toughness, defined as the material's ability to absorb energy without fracturing, is another important feature. The D_R parameter can be used as an indicator of toughness. Figure 22b illustrates the D_R parameter for all evaluated mixtures after short- and long-term oven aging, aligning with the similar observations made for S_{app}. Figures 23a and 23b show the damage characteristic curves for all mixtures after STOA and LTOA, respectively. The position of the damage characteristic curve captures the mixture's stiffness, and notably, much lower and steeper curves were observed for LTOA mixtures than for STOA mixtures, indicating the impact of aging. Under STOA, RPM mixtures exhibited lower and shorter curves compared with D and E mixtures. Conversely, under LTOA, RPM mixtures exhibited similar or higher curves compared with D and E mixtures.

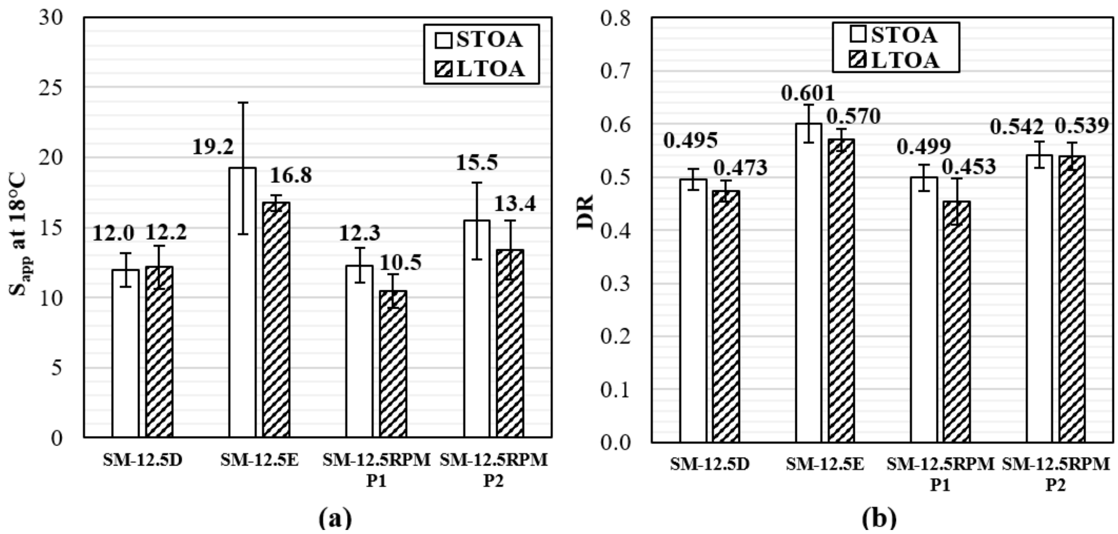


Figure 22. Cyclic Fatigue Performance Test Data of D, E, and RPM Mixtures: (a) S_{app} at 15°C; (b) D_R. I-bars indicate parameter variability ± 1 standard deviation. SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; STOA = short-term oven aged; LTOA = long-term oven aged.

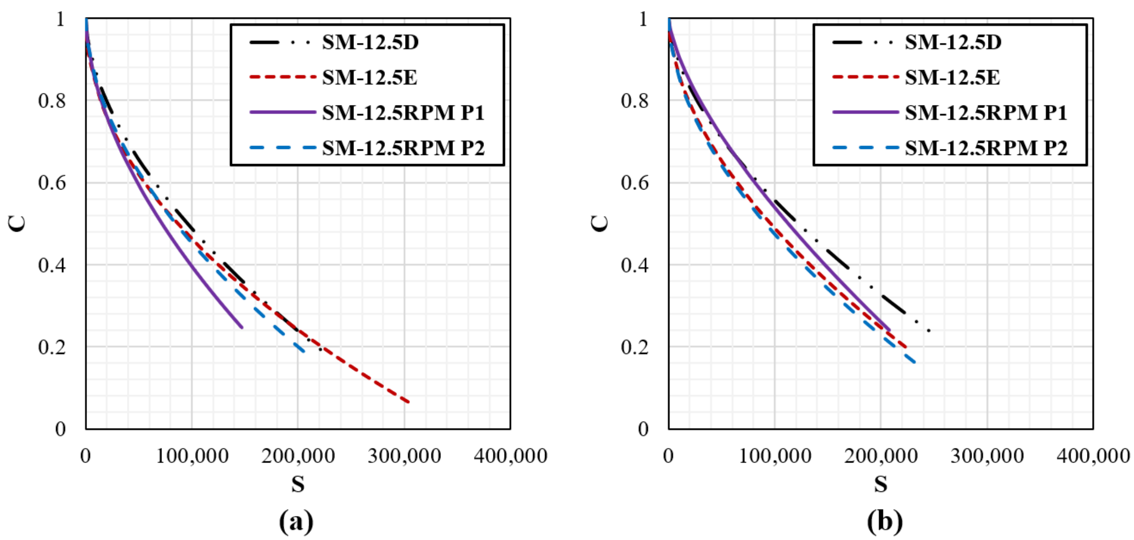


Figure 23. Cyclic Fatigue Performance Test Data of D, E, and RPM Mixtures in Terms of C versus S Curves: (a) STOA; (b) LTOA. C = material integrity; S = damage; SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; STOA = short-term oven aged; LTOA = long-term oven aged.

These observations collectively suggest that the addition of recycled plastics could enhance the cracking performance properties and characteristics of the resulting mixtures compared with D mixtures. However, these properties and characteristics do not outperform those of E mixtures.

Summary of Performance of Reheated Mixtures

Tables 7 and 8 present a summary overview of performance trends for reheated mixtures based on ranking by average parameter (refer to Table 7) and based on statistical analysis (refer to Table 8). The one-way analysis of variance (ANOVA) with Tukey's multiple comparison method at a 95% confidence interval was used for the purpose of statistical analysis. Prior to the ANOVA, the data for each test were checked for the assumptions of normality and equal variances at a 95% confidence interval. Table 7 and 8 summarize various properties of interest, including durability, resistance to rutting, and resistance to cracking, for SM-12.5RPM P1 and SM-12.5RPM P2 compared with their corresponding control/reference mixtures, SM-12.5D and SM-12.5E. Both tables showcase the changes in these properties compared with the control, denoted by arrows, indicating improvements (↑), declines (↓), or no change (↔) in each category.

Table 7. Summary of Performance Trends for Reheated Mixtures Based on the Average of Parameters

	SM-12.5D	**SM-12.5RPM P1**	**SM-12.5RPM P2**	**SM-12.5E**	**SM-12.5RPM P1**	**SM-12.5RPM P2**
Durability (Cantabro test)	C	↑	↔	C	↑	↓
Resistance to rutting:						
- IDT-HT (basic)	C	↔	↑	C	↓	↑
- IDEAL-RT (basic)		↓	↑		↓	↑
- APA rut test (intermediate)		↑	↑		↑	↑
- SSR test (advanced)		↑	↔		↑	↓
- RLT test (advanced)		↑	↑		↓	↔
Resistance to cracking:						
- IDT-CT at STOA (basic)	C	↑	↓	C	↑	↓
- IDT-CT at LTOA (basic)		↑	↓		↑	↔
- Cyclic fatigue test, STOA (advanced)		↔	↑		↓	↓
- Cyclic fatigue test, LTOA (advanced)		↓	↑		↓	↓

SM = surface mixture; D = heavy traffic; RPM = recycled plastic modified; E = extremely heavy traffic; C = control; IDT-HT = indirect tensile test at high temperature; RT = rutting tolerance; APA = Asphalt Pavement Analyzer; SSR = stress sweep rutting; RLT = repeated load triaxial; IDT-CT = indirect tensile cracking test; STOA = short-term oven aged; LTOA = long-term oven aged; ↑ = property of interest improved compared with control (highlighted in green); ↓ = property of interest declined compared with control (highlighted in red); ↔ = no change in property of interest compared with control (highlighted in green).

Table 8. Summary of Performance Trends for Reheated Mixtures Based on Statistical Analysis

	SM-12.5D	SM-12.5RPM P1	SM-12.5RPM P2	SM-12.5E	SM-12.5RPM P1	SM-12.5RPM P2
Durability (Cantabro test)	C	↑	↔	C	↔	↓
Resistance to rutting:						
- IDT-HT (basic)	C	↔	↔	C	↔	↔
- IDEAL-RT (basic)		↔	↔		↔	↔
- APA rut test (intermediate)		↔	↔		↔	↔
Resistance to cracking:						
- IDT-CT at STOA (basic)	C	↔	↔	C	↔	↔
- IDT-CT at LTOA (basic)		↑	↔		↑	↔
- Cyclic fatigue test, STOA (advanced)		↔	↔		↓	↔
- Cyclic fatigue test, LTOA (advanced)		↔	↔		↓	↓

SM = surface mixture; D = heavy traffic; RPM = recycled plastic modified; E = extremely heavy traffic; C = control; IDT-HT = indirect tensile test at high temperature; RT = rutting tolerance; APA = Asphalt Pavement Analyzer; IDT-CT = indirect tensile cracking test; STOA = short-term oven aged; LTOA = long-term oven aged; ↑ = property of interest improved compared with control (highlighted in green); ↓ = property of interest declined compared with control (highlighted in red); ↔ = no change in property of interest compared with control (highlighted in blue).

Overall, the RPM mixtures demonstrated similar durability and rutting performance properties when compared with SM-12.5D. However, the observations, when compared with SM-12.5E, suggest that the resistance to cracking might have decreased for RPM mixtures with LTOA.

Evaluation of Field Cores

Field core samples were collected from each of the four projects in Table 2 during construction. Core locations were randomly stratified along the length and width of the section. Table 9 summarizes the in-place layer thicknesses, air void levels, and permeability values. No cores were taken for SM-12.5D; therefore, no data are presented in this report. The in-place density of E mixtures was higher than that of RPM mixtures (SM-12.5RPM P1 and SM-12.5RPM P2). Note that a thicker layer was measured for SM-12.5RPM P1. This could be due to the challenge in compacting and reaching the density of mixtures delivered with the first few truckloads, leading to a probably thicker surface layer. The average permeability values, presented in Table 9, include only the values determined for cores with an air void level equal to or lower than 7.0%. Overall, observed higher permeability values included the SM-12.5RPM P1 and SM-12.5RPM P2 when compared with the SM-12.5E mixture. It should be reminded that no SM-12.5D cores were collected during this trial; therefore, the SM-12.5D row shows --, meaning “no data.”

Table 9. Summary of In-Place Layer Thickness, Air Void Level, and Permeability for Core Samples

Mixture Type/Property Measured	Layer Thickness (mm)			In-Place Air Voids (%)			Permeability (*10^{-5} cm/s)[a]		
	Avg.	CI	Target	Avg.	CI	Range	Avg.	CI	Target
SM-12.5D	--	--	--	--	--	--	--	--	150
SM-12.5E	35.8	5.5	38.1	8.9	2.6	6.3 to 11.6	4.0	3.8	
SM-12.5RPM P1	48.8	1.6	38.1	8.1	1.0	7.1 to 9.2	160.0	124.2	
SM-12.5RPM P2	36.2	2.7	38.1	7.5	0.8	6.7 to 8.3	111.0	76.9	

Avg. = average; CI = 95% confidence interval; SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified; -- = no data.

[a] The average permeability includes only the values determined for cores with an air void level equal to or lower than 7.0%.

Figure 24a shows the CT index values of all cores by mixture type. The 150-mm-diameter cores had a thickness lower than the typical thickness of 62 mm. The research team acknowledges the variation that might be induced by high variations from the target heights; therefore, the data generated were used for comparison purposes, especially with plant-produced, laboratory-compacted specimens, to assess the impact of specimen preparation type (laboratory vs. field compaction) and other components such as in-place densities. All mixtures had values significantly higher than those measured in the laboratory, regardless of the specimen type (Design, Non-reheats, Reheats, Reheats-LTOA). Concerning the mean/average values, SM-12.5E had a higher CT index average value when compared with RPM mixtures.

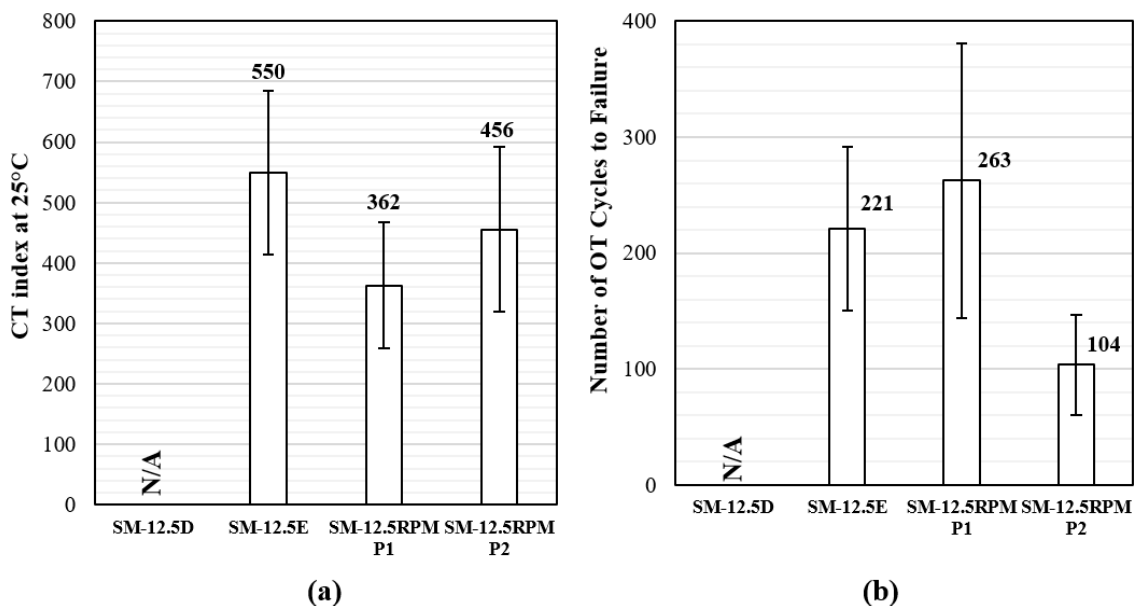


Figure 24. Cracking Performance Test Data of E and RPM Field Cores: (a) IDT-CT; (b) Texas OT. I-bars indicate parameter variability ± 1 standard deviation. SM = surface mixture; E = extremely heavy traffic; RPM = recycled plastic modified; IDT-CT = indirect tensile cracking test; OT = overlay test; CT = cracking tolerance; N/A = not available.

Figure 24b shows the number of cycles to failure at 25°C for the cores of all evaluated mixtures. No cores were taken for SM-12.5D; therefore, this report contains no data for this evaluation. A higher number of OT cycles to failure indicates better resistance to reflective cracking. A similar number of OT cycles to failure was observed for SM-12.5E and SM-

12.5RPM P1; however, a lower number of OT cycles to failure was observed for SM-12.5RPM P2 when compared with SM-12.5E. Note that the OT test is well known for its high variability.

The resistance of the evaluated mixtures to cracking initiation (using G_c) and cracking propagation (using CPR) was further analyzed using the first cycle of OT data (Garcia et al., 2016). A greater G_c value indicates that the evaluated mixture is tough and requires high initial energy to initiate a crack. On the other hand, a greater CPR value indicates that the evaluated mixture is more susceptible to cracking (a fast crack propagation indicates a shorter reflective cracking life). Figure 25 shows a design interaction graph plotting G_c vs. CPR for the E and RPM evaluated field cores. Four categories were identified on this interaction plot, including Tough-Crack Resistant, Tough-Crack Susceptible, Soft-Crack Resistant, and Soft-Crack Susceptible. A preliminary threshold for a CPR of 0.5 was proposed by Garcia et al. (2016). Also, preliminary limits for G_c were identified: An upper limit of three to screen the asphalt mixtures with high brittleness potential and a lower limit of one to guarantee a minimum stability under traffic of the evaluated mixtures. Note that these thresholds were used for comparison purposes only. Independent efforts should consider defining new thresholds specifically for E and RPM mixtures. Figure 25 shows all SM-12.5E and SM-12.5RPM P1 cores had a CPR value lower than 0.5, indicating promising resistance to reflective cracking. Moreover, SM-12.5E and SM-12.5RPM P1 cores had a G_c from 1 to 3, indicating a promising resistance to crack initiation. SM-12.5RPM P1 showed the greatest soft-crack-resistant behavior, possibly due to the relatively higher resultant binder content since P1 was added to the mixtures without replacing the virgin asphalt binder. SM-12.5RPM P2 showed the greatest soft-crack-susceptible behavior among the evaluated mixtures, likely because of the full replacement of the virgin asphalt binder in P2. This raises a significant question: Which should be considered when designing RPM mixtures, complete or no replacement of virgin asphalt binder?

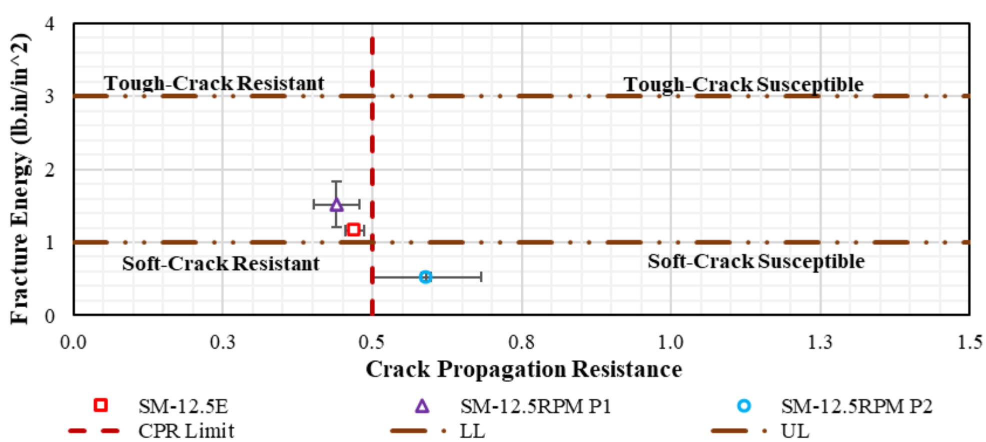


Figure 25. Cracking Performance Test Data for OT of E and RPM Field Cores at 25°C in Terms of Interaction Plot. I-bars indicate parameter variability ± 1 standard deviation. CPR = crack propagation resistance; LL = lower limit; UL = upper limit; SM = surface mixture; E = extremely heavy traffic; RPM = recycled plastic modified.

Mechanistic-Empirical Simulations

Mechanistic evaluations were conducted using FlexPave for the four pavement structures ((i) through (iv)) illustrated in Figure 5. Figures 26a and 26b illustrate (as an example) the rutting performance, measured as total rut depth progression over a 30-year lifespan, for the evaluated mixtures in Structures (i) and (iv) respectively. It is important to highlight that the only variation made for each pavement structure was in the material selected for the surface layer (SM-12.5D vs. SM-12.5E vs. SM-12.5RPM P1 vs. SM-12.5RPM P2). In all cases, there was a rapid increase in rutting depth within the initial 2 years, followed by a gradual and consistent rate of rutting depth throughout the analysis period. Among all the evaluated mixtures and regardless of the pavement structure, SM-12.5RPM P1 exhibited the lowest rutting performance. SM-12.5RPM P2 demonstrated similar or slightly inferior rutting performance compared with SM-12.5D, regardless of the pavement structure. Note that the results presented and discussed below are based on laboratory simulations without calibration to real-world conditions. Therefore, comparative analysis was the sole approach employed.

However, VDOT is more concerned about pavement cracking than rutting (Diefenderfer et al., 2021). Therefore, VDOT uses cracking (percent damage) curves as the sole criterion to determine the lifespan of each asphalt mixture. For example, Figures 27a and 27b illustrate the fatigue performance in terms of top-down damage for Structure (i) and total damage for Structure (iv) over a 30-year span. These curves serve as hypothetical examples. The specified percent damage curves for each pavement section were used to establish the maintenance interval for the four evaluated mixtures. SM-12.5D was the comparator in this case, with its lifespan set at 10 years. VDOT typically replaces asphalt roadway surface mixtures on an 8-to-12-year schedule through mill and fill maintenance. The amount of damage exhibited by the comparator mix at the 10-year mark was determined from the damage curves. To find maintenance intervals for other mixtures, interpolation was used to identify the number of years corresponding to the same damage level as the comparator at the 10-year threshold. The corresponding percentage damage was then determined. Table 10 shows a summary of the intervals and the percent extension for the comparator.

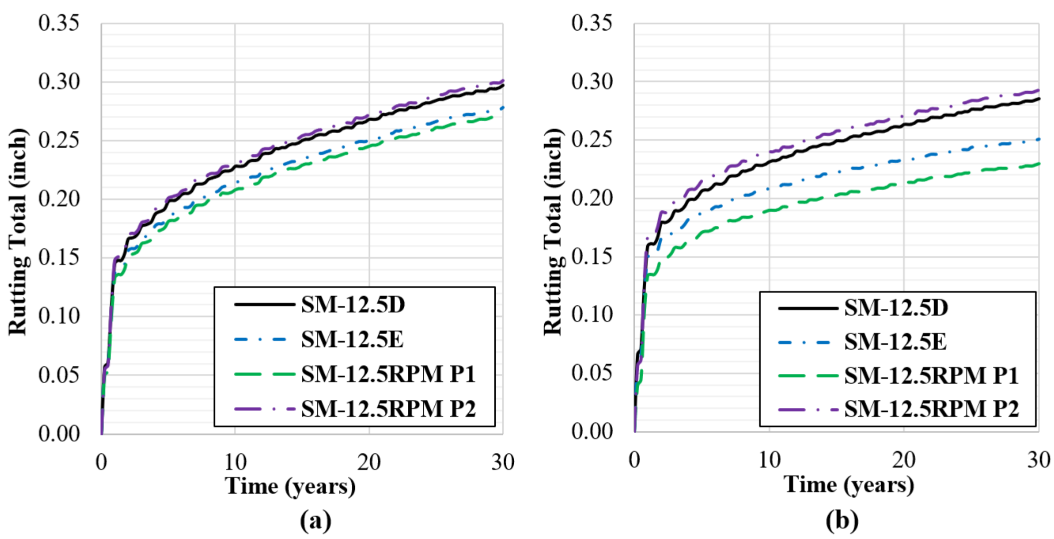


Figure 26. FlexPave Simulation Total Rutting Performance Results: (a) Structure (i); (b) Structure (iv). SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified.

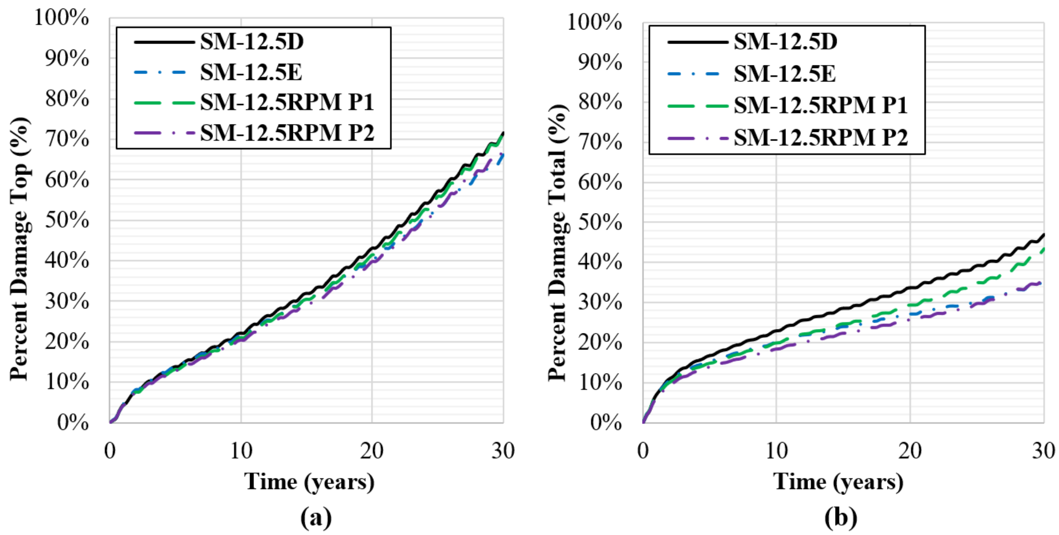


Figure 27. FlexPave Simulation Fatigue Performance Results: (a) Structure (i); (b) Structure (iv). SM = surface mixture; D = heavy traffic; E = extremely heavy traffic; RPM = recycled plastic modified asphalt.

Table 10. Summary of Hypothetical Projected Performance Lifespan Based on 10 Years SM-12.5D Reference

Structure / Mix ID	**Performance Life (years) / Hypothetical Extension Based on 10 Years Reference (%)**			
	SM-12.5D	**SM-12.5E**	**SM-12.5RPM P1**	**SM-12.5RPM P2**
i	10.000 / ref.	10.464 / +4.64%	10.605 / +6.05%	10.895 / +8.95%
ii	10.000 / ref.	10.948 / +9.48%	10.924 / +9.24%	11.664 / +16.64%
iii	10.000 / ref.	10.518 / +5.18%	10.609 / +6.09%	10.744 / +7.44%
iv	10.000 / ref.	13.750 / +37.50%	13.338 / +33.38%	16.450 / +64.50%

SM = surface mixture; D = mixture designation; E = extremely heavy traffic; RPM = recycled plastic modified.

Overall, RPM mixtures hypothetically demonstrated similar and/or better cracking and rutting predicted performance when compared with D and E control/reference mixtures, leading to a possible extension in the performance life based on the results of the ME simulations in this study and within the limitations mentioned previously.

Non-Destructive Pavement Testing (NDT)

NDT was performed on Old Stage Road. FWD and GPR tests were conducted to assess the strength and uniformity of the pavement structure, enabling fair comparisons among the performance of SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2 surface layers. Note that SM-12.5D was placed on a road near Old Stage but was not subjected to FWD and GPR testing. FWD data were not presented here; rather, the measured deflection values indicate the presence of a structurally strong pavement. Similarly, GPR data were not included in this report; however, the analysis of the measurements indicated consistency in the different layers and sub-layers of the pavement structure throughout Old Stage Road.

Ride Quality Results and Analyses

The ride testing results for Old Stage Road are presented in Figure 28. Figure 29 displays the boxplot of IRI, showing that the average IRI values for SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2 were 156, 97, and 83, respectively. Observation of RPM sections were that they looked smoother than the E section. That observation indicates that the addition of recycled plastic no negative impact on the pavement's roughness.

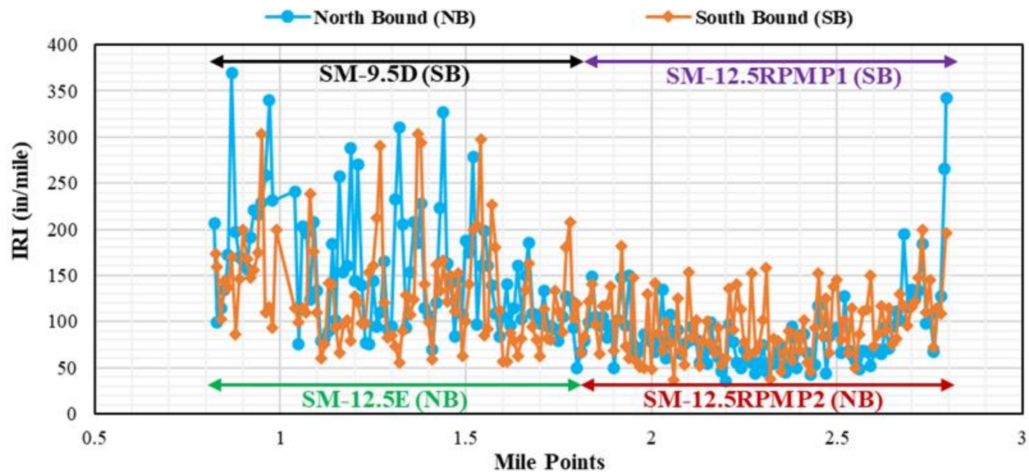


Figure 28. International Roughness Index (IRI) Results for Old Stage Road

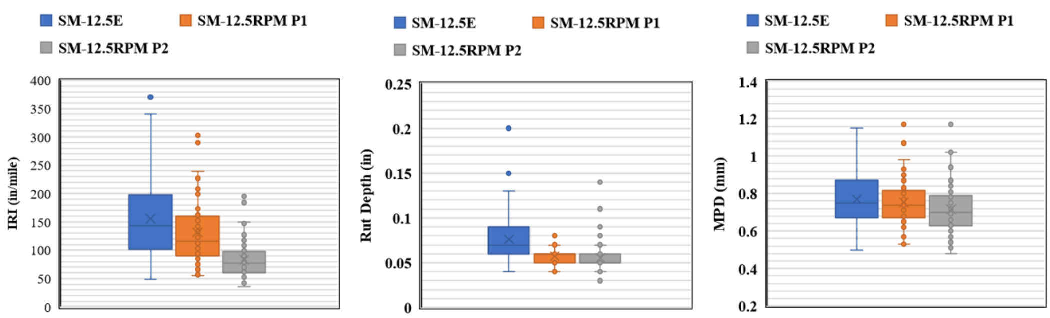


Figure 29. Box Plots of Results for Old Stage Road: (a) International Roughness Index (IRI); (b) Rut Depth; (c) Mean Profile Depth.

Rut Depth Results and Analyses

Figure 30 shows the rut depth results for Old Stage Road. Lower rut depth average values of 0.076, 0.057, and 0.055 inch were observed for SM-12.5E, SM-12.5RPM P1, and SM-12.5RPM P2, respectively (refer to Figure 29b). RPM sections exhibited lower rut depth values when compared with E section. Those values indicate that the addition of recycled plastic is expected to enhance the resistance to rutting in the field when compared with VDOT's typical mixtures.

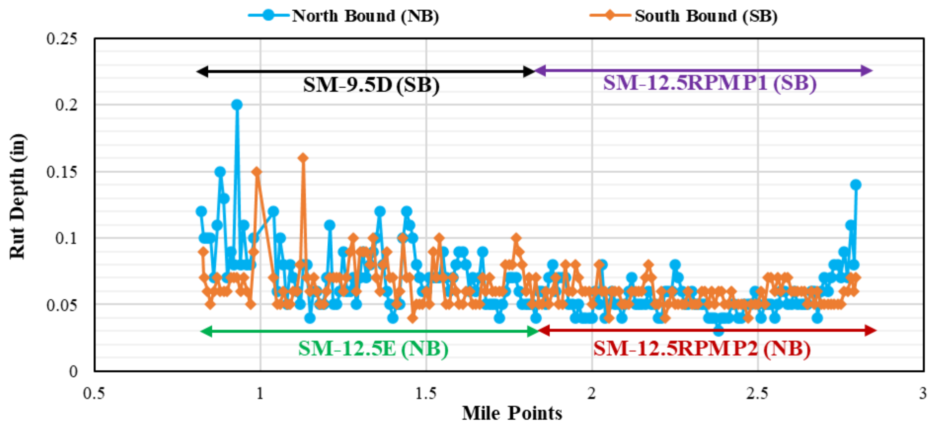


Figure 30. Rut Depth Results for Old Stage Road

Mean Profile Depth Results and Analyses

The MPD results for Old Stage Road are shown in Figure 31. MPD values are associated with macrotexture. MPD average values of 0.769, 0.752, and 0.717 mm were observed for SM 12.5E, SM-12.5RPM P1, and SM-12.5RPM P2, respectively. Those values are comparable with typical values for surface asphalt pavements in Virginia (refer to Figure 29c) (Boz et al., 2023a). RPM sections exhibited similar macrotexture to the E section, indicating that the addition of recycled plastic does not negatively impact the pavement's macrotexture.

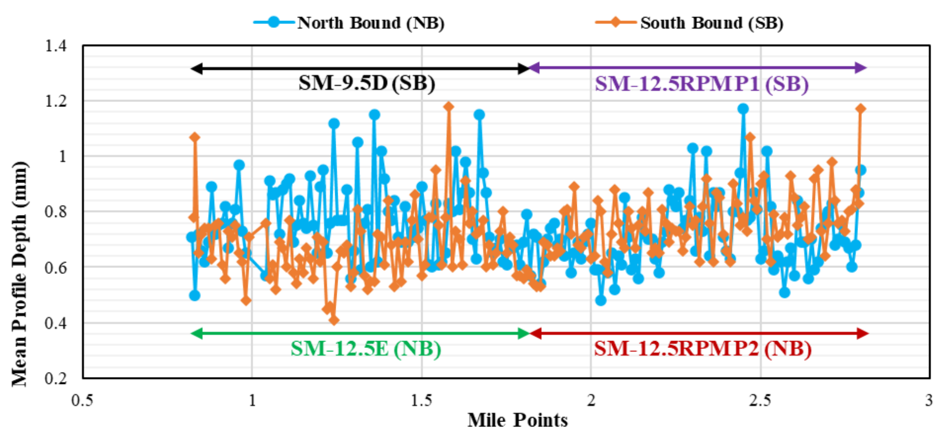


Figure 31. Mean Profile Depth (MPD) Results for Old Stage Road

In-Service Conditions of Evaluated Pavement Structures

The E and RPM sections of Old Stage Road are in very good condition after 2 years, as Figure 32a shows. Figure 32b shows the CCI data for Old Stage Road, both before and after paving and is available for only the northbound (SM-12.5E and SM-12.5RPM P2); however, the southern bound (SM-12.5RPM P1) also appears to be in excellent condition. No major distresses have been reported for these sections. Since the evaluated sections were constructed during the 2021 construction season, the 2-year performance data and corresponding observations are still considered preliminary. The research team will continue to monitor the performance of these sections and others constructed during the 2022 and 2023 paving seasons.

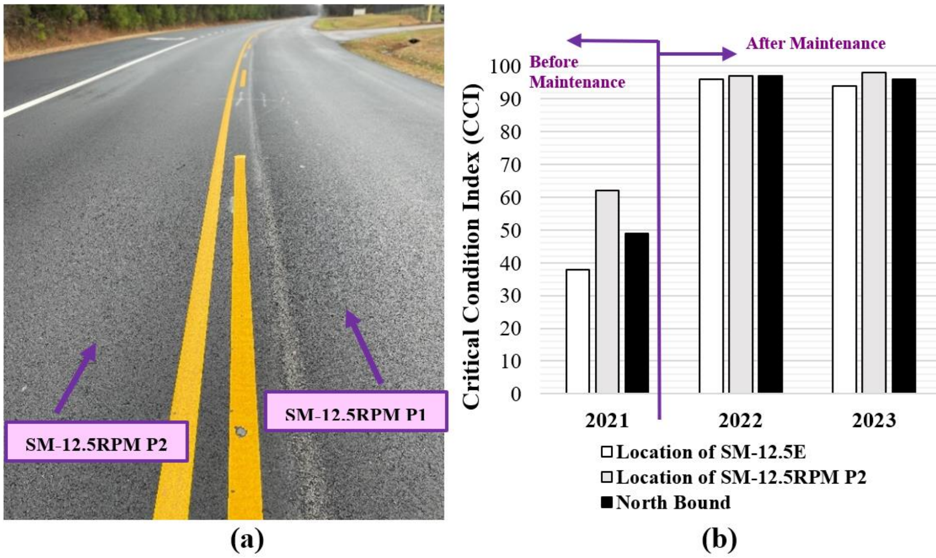


Figure 32. (a) Photograph Taken 24 Months Post-Paving; (b) Critical Condition Index for Years 2021–2023

Microplastic Evaluation

This section outlines the results of the microplastics evaluation, including TGA and FTIR results of the plastic additives alone (i.e., P1 and P2) and those of the material recovered from Cantabro testing (i.e., P1-Ext and P2-Ext). Results collected from the plastic additives alone were used as reference data to inform the quantification (via TGA results) and identification (via FTIR results) of microplastics present in P1-Ext and P2-Ext samples.

Thermogravimetric Analysis

P1 Additive Reference Thermograms

Figure 33 provides reference thermograms generated from the P1 plastic additive and binder recovered during extraction. In addition, Table 11 shows the characteristic temperatures associated with each material. As shown, all ten colors produced very prominent singular thermal events at an average characteristic temperature of 450±9.9°C. Although these thermograms are generally consistent, translucent yellow and white samples vary from the others with characteristic temperatures occurring at about 430°C. Although it is only a slight decrease in temperature, the decrease does supports previous experimental testing that included FTIR-ATR, and indicates that these particles were polypropylene. Considering that the P1 plastic is a recycled material, some level of intermingling of other plastic types would be expected.

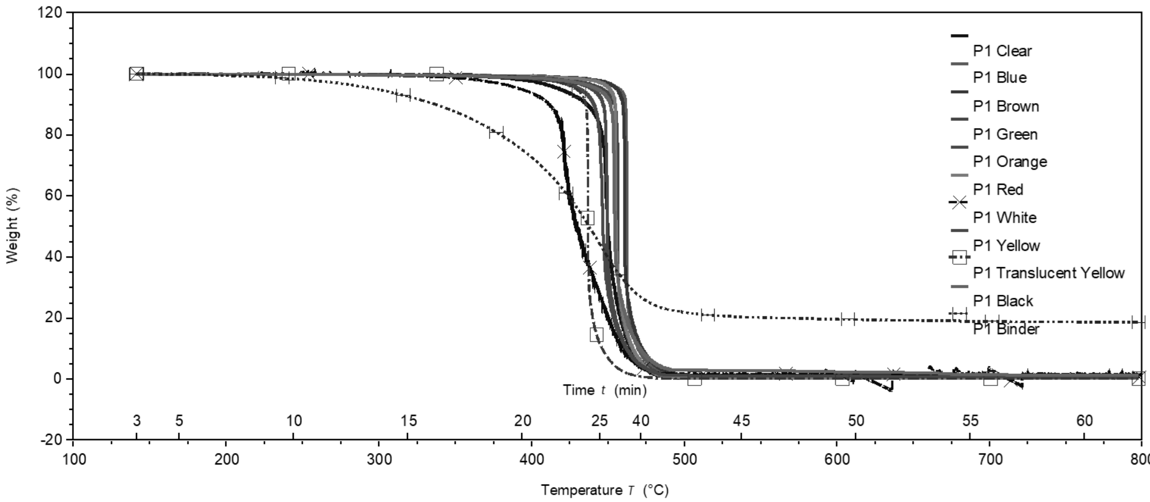


Figure 33. Reference Thermograms Generated from P1 Plastic Including Recovered Extracted Binder. Data provided in the inset table represents the characteristic temperature of each material.

Focusing on the binder thermogram result shown in Figure 33, the material's characteristic temperature is similar to that of the P1 additive, at 426°C. However, the associated thermal event occurs over a much broader temperature range, starting at around 380°C and ending just under 475°C, as Table 11 shows. Furthermore, although all the P1 samples experienced almost 100% mass loss by the end of the test (ranging from 98% to 99.89%), the binder sample resulted in an 81.5% mass loss by the end of the test.

Table 11. Starting, Ending, and Characteristic Temperatures of the Thermal Decomposition of P1 Plastic by Color and the Extracted Binder

Material	Decomposition Start	Decomposition End	Characteristic Temp
Black	453.6°C	454.9°C	454.4°C
Blue	462.1°C	462.3°C	462.2°C
Brown	460.6°C	461.2°C	460.9°C
Green	456.2°C	456.8°C	456.5°C
Orange	443.7°C	449.8°C	446.8°C
Red	454.9°C	455.8°C	455.5°C
White	414.4°C	443.2°C	431.2°C
Yellow	448.8°C	450.1°C	449.5°C
Translucent Yellow	436.9°C	437.4°C	437.1°C
Clear	445.7°C	454.0°C	449.9°C
Binder	379.7°C	474.7°C	426.2°C

Although these results show that the characteristic temperature of the binder portion of the asphalt matrix does have some overlap with the P1 plastic. The two components can be readily distinguished from one another based on the overall shape of the thermograms with the former generating more gradual mass loss curve. When considering results collected from extracted samples, this overlap also indicates that unextracted binder could contribute slightly to the mass losses associated with microplastics. However, this contribution is likely very minor given that the sample material contained less than 6.6% binder by weight.

P2 Additive Reference Thermograms

By comparison with the P1 reference thermograms, those generated for the P2 additive are more complex. As can be seen in Figure 34, three distinct thermal events occur at about 367°C, 427°C, and 466°C. These results indicate that the material is a mixture of three different components, including PET plastic, consistent with the manufacturer-provided information. Considering the characteristic temperatures developed by Yu et al. (2019), the second mass loss event, with a characteristic temperature of 427°C, can likely be associated with the decomposition of PET in the mixture. From the results collected from the three reference tests, the P2 additive is made up of 30% PET plastic with a characteristic temperature of 426 ± 2.7°C.

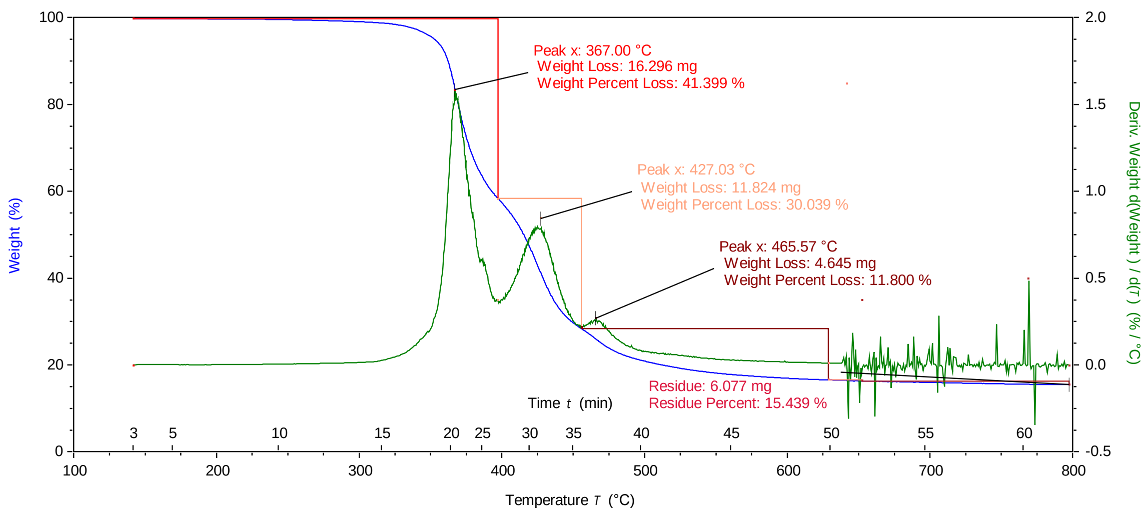


Figure 34. Reference Thermogram of the P2 Plastic Additive as Received from the Manufacturer

Although a thorough characterization of P2-Ext samples could not be conducted with FTIR, preliminary results of the P2 additive support these findings. As shown in the Gram-Schmidt profile at the top of Figure 35, three pulses of higher intensity spectra were detected at times corresponding approximately to the three mass loss events depicted in Figure 34. When compared with commercial reference libraries, the spectra collected at about 35 minutes closely matched (with a 74.99 match value) to that of benzoic acid, a primary product of the pyrolysis of PET plastic (Artetxe et al., 2010). The remaining two events could not be reliably identified with the commercial libraries currently available at VTRC.

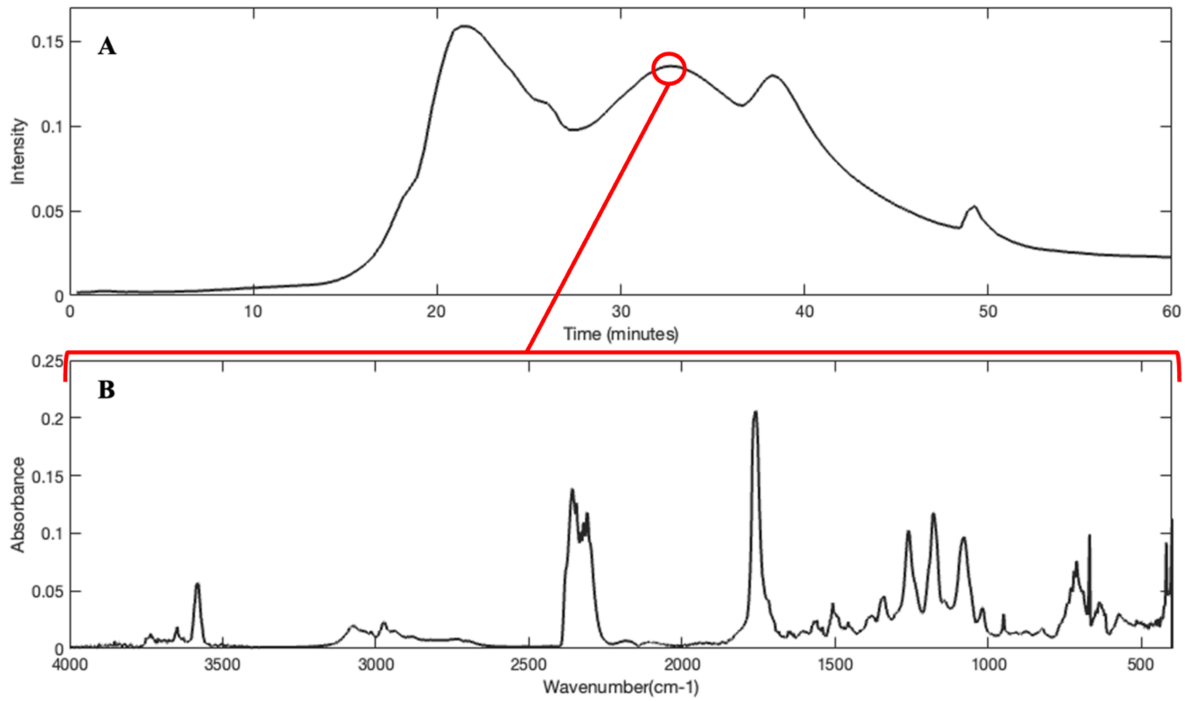


Figure 35. P2 Additive Gram-Schmidt Intensity Profile (A) and Associated FTIR Spectrum (B)

P1-Ext Thermograms

Thermograms of the P1-Ext varied based on the evaluated particle size. The larger particles (i.e., those ≥ 1.18 mm) exhibited one distinct mass loss event around the characteristic temperature of the P1 additive (Figure 36). Both the larger particles and those smaller than 1.18 mm showed two additional and distinct events at higher temperatures (approximately 590°C and 715°C). These results suggest the presence of other components in the material. However, the composition of this material could not be determined as its concentration was below the detection limits of the FTIR equipment. Nevertheless, thermograms collected from the control mix also exhibited these higher temperature events, with none found around the characteristic temperature of the P1 plastic. These results support the use of these characteristic temperatures (and the associated mass loss) for the quantification of microplastics in the material. These higher temperature events could be related to the pyrolysis of fine aggregates present in the material.

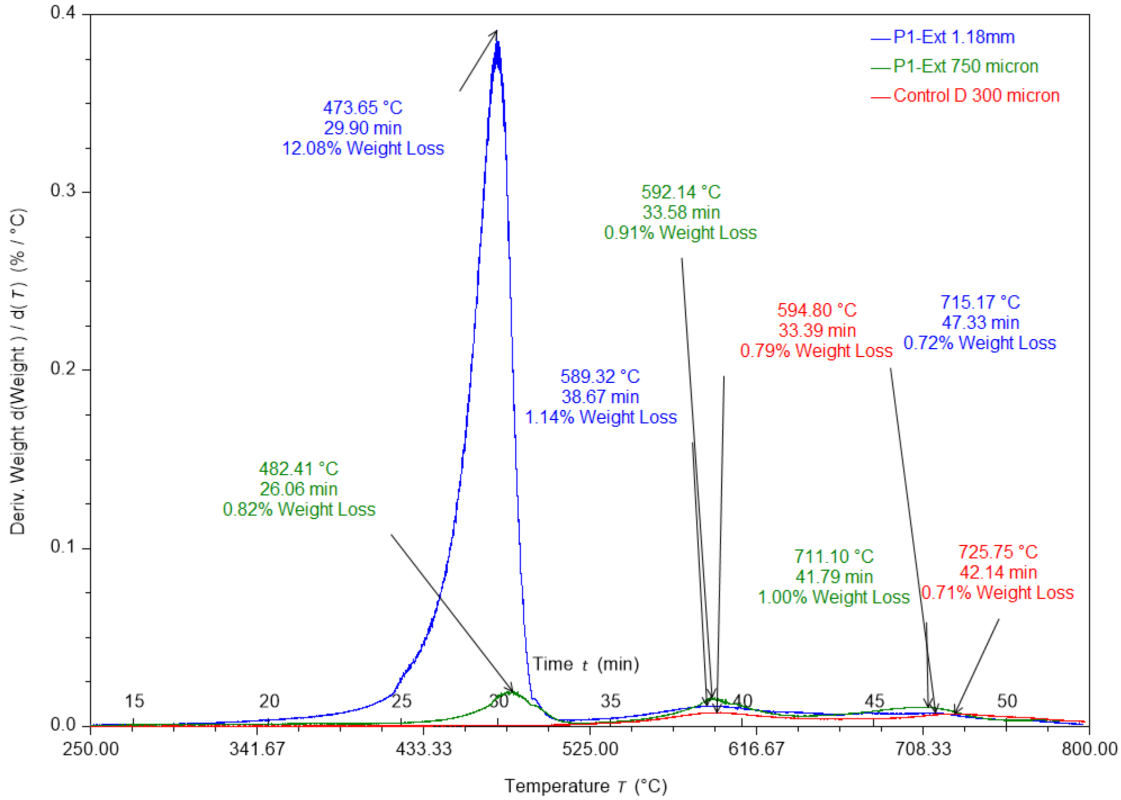


Figure 36. Thermograms of 1.18 mm Particle Size (Top) and 75 µm Particle Size (Bottom) P1-E Samples

For each of the evaluated particle sizes, Figure 37 presents mass loss data collected at the characteristic temperature of the P1 additive extracted from each P1-Ext and Control Mix TGA. Note that this data is expressed in units of mg/g, indicating the amount of mass lost per gram of material. Average concentrations range from 2.03 mg/g to 7.32 mg/g, with smaller particle sizes (less than 1.18 mm) containing higher concentrations than the larger particles. Among these smaller particle sizes, no clear trend existed, with the highest concentration detected in the 75 µm particle size and the lowest in the 300 µm particle size.

These results indicate that although the P1 additive primarily consisted of particles greater than 0.8 mm, the P1 material present in the abraded P1-Ext material was considerably smaller. The reason for this could be a result of the heating, mixing, and compaction process or an artifact of using Cantabro testing residuals as a representative sample material. Additionally, the results from the Control Mix indicate that the solvent extraction process was effective at removing binder from material of all sizes with no mass loss detected at the binders' characteristic temperature in all samples.

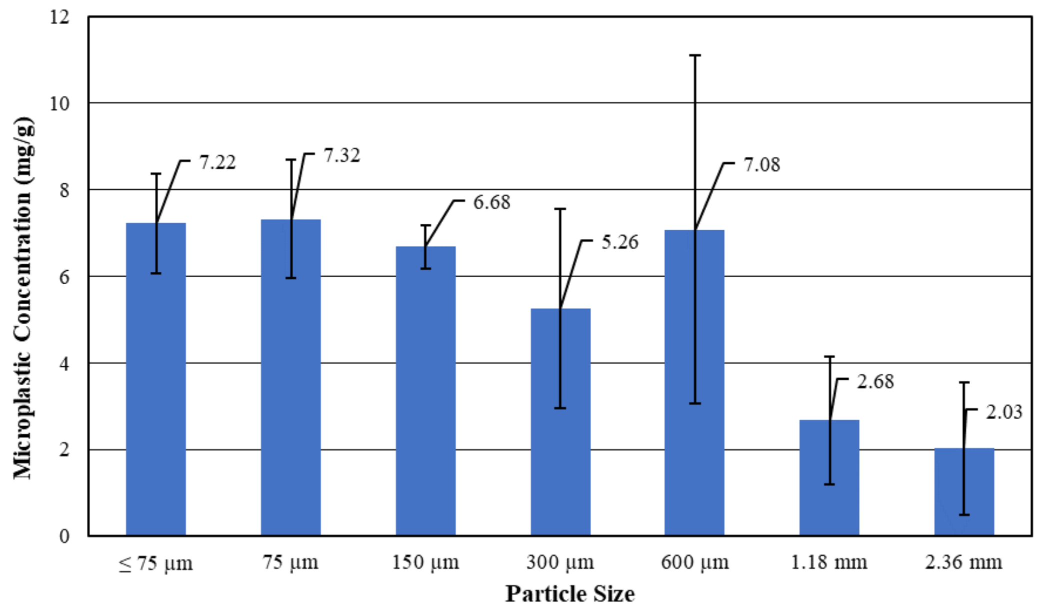


Figure 37. Average P1 Concentration in Each Particle Size for P1-Ext. Error bars represent the standard error of the dataset.

P2-Ext Thermograms

By comparison with the P1-E samples, a mass loss event associated with the P2 characteristic temperature (426 ± 2.7°C) was detected in only 1 of the 4 75 µm subsamples. This mass loss corresponded to a "plastic" concentration of 2.40 mg/g. The remainder of the samples produced no events in the range of the P2 characteristic temperature. However, higher temperature events similar to those in the P1-E and Control samples were also found in P2-E samples as Figure 38 shows.

These results could be due to two different factors, either individually or together. First, during solvent compatibility testing the P2 additive showed very poor compatibility with all the solvents tested, becoming soft and/or liquid readily on contact. Therefore, any discrete particles of P2 present in the abraded material could have been removed during the solvent extraction of the binder. Alternatively, the P2 additive could have been thoroughly dissolved and incorporated into the binder as intended and again extracted away. Further analysis of this material will require alternative sample preparation methods or analytical techniques.

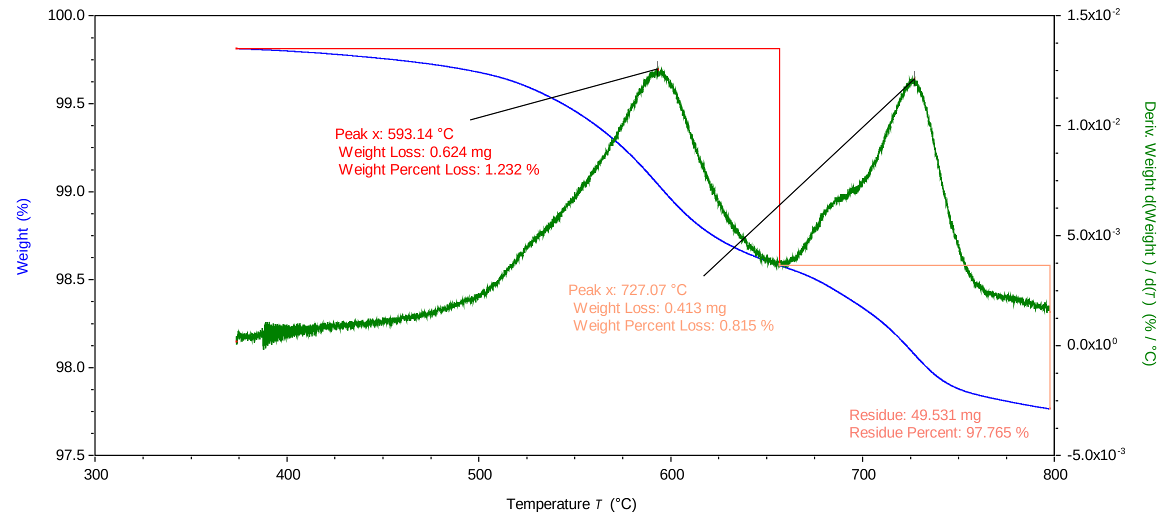


Figure 38. Thermogram of 75µm P2-Ext Material

Fourier Transform Infrared (FTIR) Analysis

Note that although FTIR spectrometry can reliably provide a chemical "fingerprint" of a material, it is not particularly well-suited for determining material concentrations. Therefore, the purpose of these FTIR experiments was to provide additional information to support the hypothesis that the mass loss occurring during the TGA runs is attributed to the pyrolysis of microplastic particles present in the material. This attribution was made by comparing FTIR results with a library of known references. As noted previously, only results from the P1 additive are provided in this report due to a mechanical issue with the laboratory equipment. However, based on the results from the TGA experiments of the P2-Ext samples, it can be reasonably expected that the associated FTIR results would be inconclusive at best.

Figure 39 provides reference spectra collected from the P1 additive and are agree with those found in Yu et al. (2019). The figure illustrates that overall, each particle color shows reasonably consistent overlap with peaks representative of hydrocarbons at about 3000 cm-1 and characteristic peaks in the fingerprint region (1000 cm-1 to 1600 cm-1) at around 1475 cm-1 and 1350 cm-1, along with a prominent peak at 875 cm-1. These results indicate that these particles are made of a different material than the other particles in the additive. However, these differences and those observed in all of the P1 reference spectra collected were not significant enough to distinguish between particle colors. These similarities were expected given the limitations of vapor phase FTIR analysis identified in the literature.

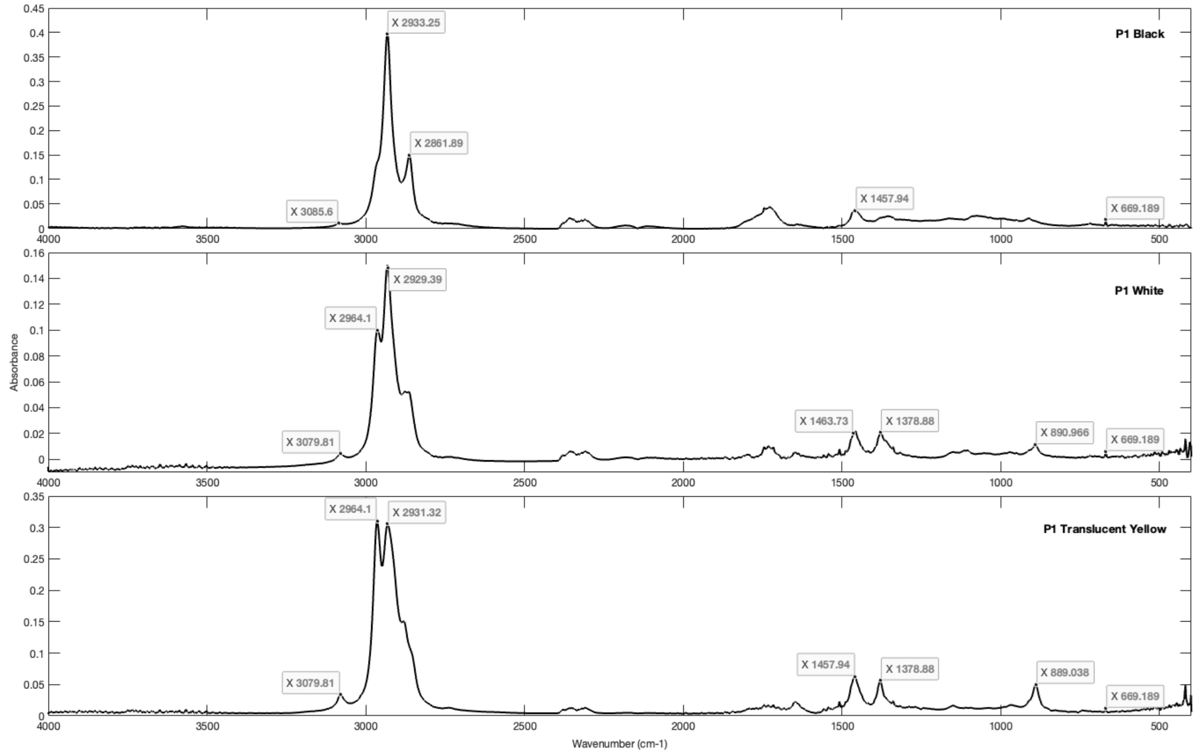


Figure 39. P1 Plastic Additive Reference Library for Predominant Particle Colors. Red and green boxes highlight some of the functional groups and regions of interest in the spectra.

Comparing the P1 additive reference spectra with that of the recovered binder from P1-Ext, a significant overlap occurred at certain wave numbers. Using the spectrum collected from particles of white P1 additive as an example in Figure 40, the binder shares similar peaks around 2950 cm-1, 2800 cm-1, 1475 cm-1, and 1350 cm-1. However, the binder spectrum does exhibit an additional peak at about 1550 cm-1 and does not have the peak at 880 cm-1 found in the P1-Ext spectra. Given that both PE and asphalt binder are hydrocarbons, these similarities are to be expected.

The overlapping binder and P1 spectra were initially concerning in terms of verifying the TGA results. However, as can be seen in Figure 40, FTIR spectra collected from the Control Mix (green line) showed no measurable hydrocarbon spectra in all of the particle sizes. These results indicate that the solvent extraction step was effective at removing the majority of the bituminous material.

Focusing on P1-E samples, spectra collected 26 minutes into each TGA run (correlating to the characteristic temperature identified earlier) were used to evaluate the composition of the evolved gases. Figure 41 depicts the spectra collected from each of the particle sizes evaluated. As can be seen in Figure 41, the collected spectra strongly overlap with each other except for the spectrum associated with the 75µm and 150 µm particle sizes which show no significant peaks.

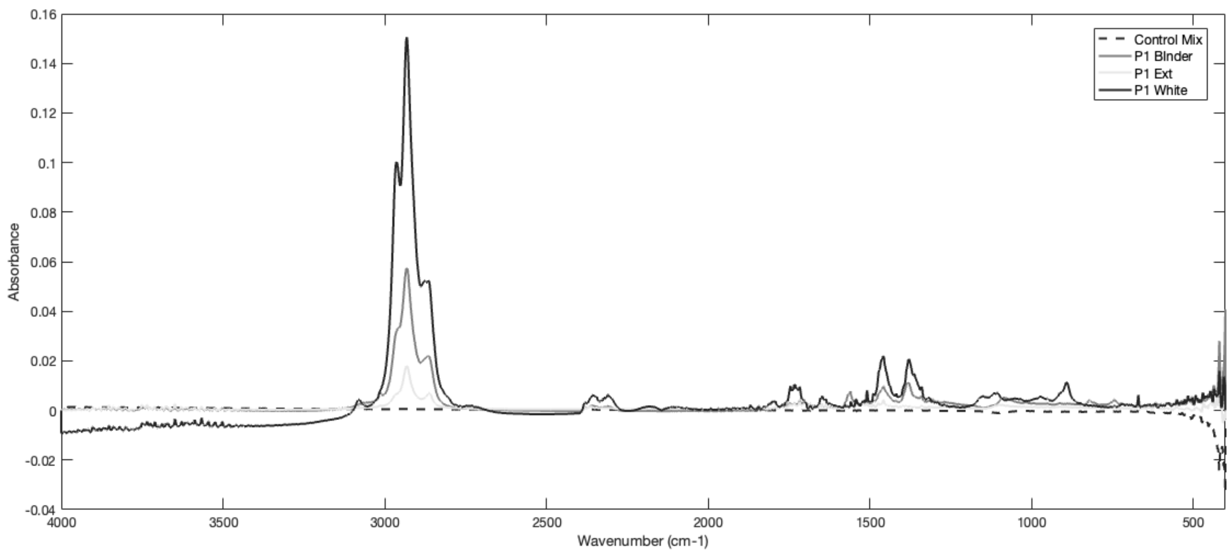


Figure 40. Infrared Spectra Collected at the P1 Characteristic Temperature from White P1 Additive, Recovered Binder from P1-Ext, and Spectra Collected from 75µm Particles Extracted from the Control Mix and P1-Ext

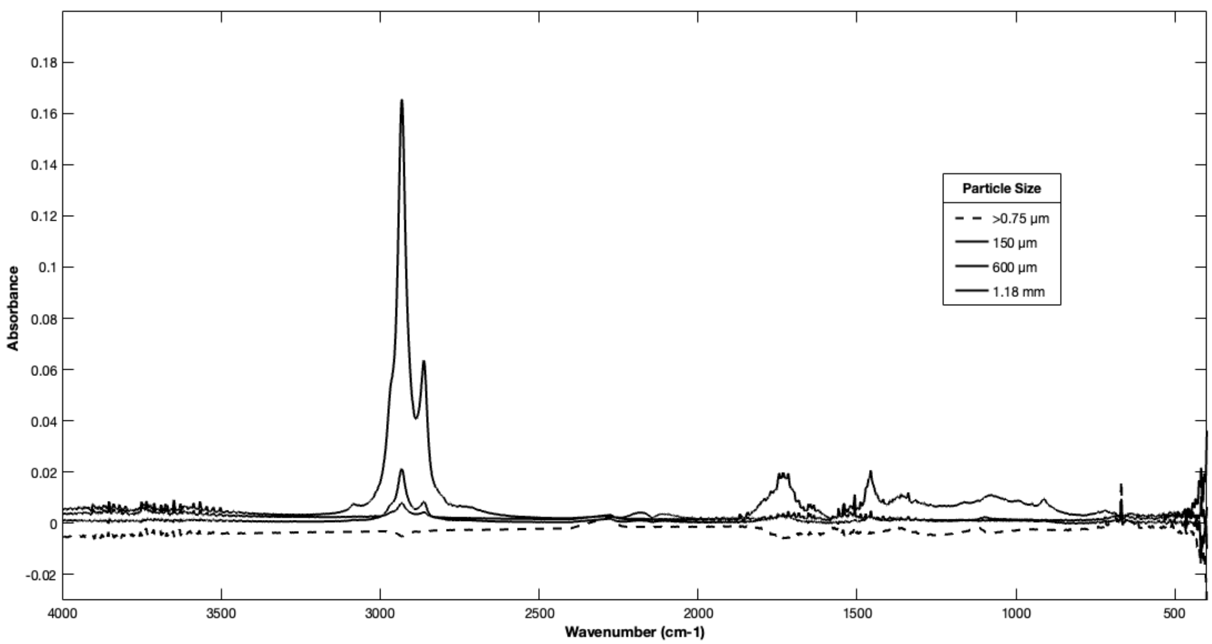


Figure 41. P1-Ext Infrared Spectra Collected at the 26th Minute of the TGA Run. Note that spectral data associated with CO2 (i.e., 2400 to 2200 cm^{-1}) have been omitted from all spectra for clarity.

The variability in relative absorbances between particle sizes is likely due to the varying concentrations of each subsample (not to be confused with the results reported in Figure 37). Samples smaller than 1.18 mm were tested directly, whereas those from the 1.18 mm and 2.36 mm particle sizes were hand-sorted under a microscope to isolate suspected microplastic particles from the aggregate. This sorting process was necessary to reduce the mass of the subsamples within the TGA pans' capacity, but hand sorting also effectively concentrated these samples. As a result, FTIR spectra of the smaller particle sizes are not as distinct as those of the larger particles and, in some cases, fall below the detection limits of the instrumentation. Potential solutions include additional sorting of the smaller particle sizes (though this presents challenges) or substituting FTIR analysis with a more sensitive technique such as MS.

When comparing these sample spectra with those of the previously developed reference library, the extracted sample spectra agree well with the library. Samples from the 1.18 mm particle size closely matched the P1 reference spectra with a match value of up to 98.8. Similarly, samples of the 75 µm particle size also exhibited a strong match with P1 reference spectra, with a match value of up to 75. Match values indicate the degree of similarity between an unknown spectrum and a library spectrum, with 100 indicating a perfect match (Thermo Electric Corporation, 2006). These match values further confirm that the mass loss values presented in Figure 37 represent the P1 additive still present in the sample material as discrete particles.

Thoughts Associated with the Potential Release of Microplastics

Although the test results indicate that discrete particles of the P1 additive are still present in the asphalt matrix after heating, mixing, and compacting, their presence does not necessarily mean that using RPM asphalts in the field will be a source of microplastics in the environment. The objective of this phase of the study was to develop methods of identifying microplastics present in material abraded from the pavement surface. As this is a novel material, the existing literature on this topic is very limited. Therefore, this objective was achieved through a laboratory scale investigation. Although the samples collected from the Cantabro testing can be considered representative samples, it would not be fair to consider them representative of material abraded by typical wear and tear from vehicular traffic. Rather, the aggressive nature of the Cantabro test generates material more representative of material created during milling, pulling material from deeper within the bulk of the sample. To determine if regular wear and tear of this material generates similar results required a rigorous field investigation.

That being said, the results show that the methods outlined previously show promise for application to field samples of soil and stormwater runoff collected from the trial sections with some modifications. In particular the limitations of the FTIR analysis to differentiate between polymer types needs to be addressed. Although this technique was very effective for the laboratory-based evaluation (where the polymer types and source were already known), field samples will likely contain plastics from any number of unknown sources, making microplastic source attribution difficult at best. Previous research in the literature indicates that substituting FTIR analysis with MS (i.e., TGA-MS or pyrolysis GC-MS) would be a likely solution (David et al., 2018; Mansa, 2021).

CONCLUSIONS

- *Addressing the challenges associated with integrating recycled plastics into asphalt mixtures demands further research in key areas such as sourcing, incorporation methods, material characterization, plant operations, and safety considerations.*
- *The incorporation of recycled plastics into asphalt mixtures may necessitate similar mixing and production temperatures at the plant in line with the temperatures required to produce SBS-modified mixtures, which are usually higher than those of unmodified mixtures.*

- *The addition of recycled plastics into asphalt mixtures does not necessitate any changes from the established routine practices regarding surface preparation or paving operations, except for weather and air temperature.* Standard construction practices and equipment typically used for D and E mixtures can be used for RPM mixtures. However, paving RPM mixtures may require warmer weather when compared with typical unmodified and SBS-modified mixtures.
- *The addition of recycled plastics using the wet process in asphalt binder testing or the dry process in asphalt mixture testing, and plant production simulation will yield different results and conclusions.*
- *Lessons learned from this study indicate that the method of incorporating recycled plastic, as well as the dosage, should be determined based on performance derived from asphalt binder and/or mixture testing and not solely on volumetric properties.*
- *The results of the binders tested in this study indicate that modifying asphalt binders with recycled plastics can enhance the base binder (unmodified) in terms of resistance to cracking and loss of flexibility while also reducing susceptibility to long-term aging. However, these binders did not achieve the same level of performance as SBS-modified asphalt binders when characterized according to AASHTO M 332.*
- *There will be a major impact of no, partial, or full replacement of binder when adding recycled plastic to asphalt mixtures.* Based on this assumption, furnace calibration factors should be adjusted accordingly during the mix design stage to avoid unexplained major differences from allowable tolerances, as per specifications, on the binder contents during production.
- *Based on the results for the mixtures tested in this study, modification with engineered recycled plastics could enhance the cracking performance properties and characteristics of the resulting mixtures compared with unmodified mixtures. However, the observations, when compared with E mixtures, suggest that the resistance to cracking might have decreased for RPM mixtures after long-term oven aging. Further, there was no significant difference in the performance of RPM and D mixtures based on the three levels of testing complexity considered in this study. Meanwhile, a difference was observed between RPM and E mixtures for the advanced level CF test.*
- *Based on the results of the hypothetical ME simulations in this study and within the limitations previously mentioned of the mechanistic framework used, the incorporation of engineered recycled plastics hypothetically can provide a similar or extended predicted in-service life when compared with traditional D and E mixtures.* This conclusion remains valid only after acknowledging all the limitations and assumptions made in the "Mechanistic-Empirical Simulation" section of this report.
- *Based on the results for the sections evaluated in this study, the addition of recycled plastics did not have any negative impact on roughness, resistance to rutting, and macrotexture of the corresponding pavements when compared with the SBS-modified E pavement section.*
- *Both RPM sections are in very good condition. As both sections were placed in 2021, field performance data are considered preliminary. Continued monitoring of the sections'*

performance is necessary to accurately quantify any potential cost savings in comparison with other reference mixtures, such as unmodified and polymer-modified surface mixtures.

- *Solvent extraction followed by TGA-FTIR is an effective method for quantifying discrete plastic particles present in asphalt mixtures modified with PE-based additives. However, this method is not suitable for PET-based additives due to the plastic's poor compatibility with the solvent extraction process.*
- *Discrete microplastic particles are present in the material abraded from P1 samples during Cantabro testing. However, Cantabro testing is an accelerated weathering test that produces mass loss results that are not directly proportional to a specific service time under field conditions. For this reason, it is still uncertain at what rate microplastics present in this material would be released into stormwater runoff or soil samples generated from the pilot locations.*

RECOMMENDATIONS

1. *VDOT's Materials Division and VDOT districts should consider allowing the use of RPM surface mixtures modified with engineered recycled plastic as an additional alternative to the use of conventional D mixtures on medium to high traffic volume facilities*. As specified in the "Implementation" section of this report, this consideration should be formalized by commissioning a stakeholder group to outline the necessary research steps. This recommendation is based solely on the laboratory performance properties of the material; further information is needed to fully understand the material's potential environmental effects and benefits. The data related to asphalt mixture performance characterization, discussed in this report, demonstrated similar or superior laboratory performance and initial field performance of RPM mixtures when compared with typical unmodified D surface mixtures. Note that in this study, the D mixture had 30% RAP, and the E and RPM mixtures had 15% RAP.
2. *VDOT personnel in districts where RPM mixtures were placed should continue to monitor the performance of the RPM sections evaluated in this study.* That continuance will help predict the service life of the RPM overlays evaluated in this study as the existing sections continue to age.
3. *VDOT's Materials Division, with support from VDOT's Environmental Division, should encourage VDOT districts to conduct additional field trials using RPM mixtures for the purpose of collecting more field data, benefit-cost evaluation, life-cycle assessment, and understanding the impact of using higher RAP content (up to 30 percent) with engineered recycled plastics.* Control sections with unmodified D mixtures should be included in these field trials to compare laboratory and field performance. This will help in evaluating the cost-effectiveness of using RPM mixtures in future projects when a more accurate representation of material costs is available.
4. *VDOT's Environmental Division should follow through with the research needs statement (RNS) submitted to and voted on by VTRC's Environmental Research Advisory Committee during the Fall 2022 meeting to apply the microplastic analysis methods developed during this study to field samples. Without further long-term field-based research, whether the microplastic particles identified in asphalt mixtures have the potential to be released into the environment remains unclear.* The focus of this proposed follow-up study should be to use

this study's methods on samples of stormwater runoff and soils collected from the pilot sites and other locations in Virginia. This research should aim to further improve the understanding of the fate and transport of plastics used in RPM asphalt mixtures as the basis for making informed decisions on the future use by VDOT.

5. *VDOT's Materials Division should consider investigating the use of the BMD approach for RPM mixtures in Virginia.* This effort should include selection of suitable performance tests and assessment of the tests' capability to capture the impact of plastic-based polymer modification on the performance properties of asphalt mixtures. Moreover, the effort should include determining corresponding performance-based threshold criteria in an appropriate manner to guarantee a longer performance life of these mixtures in the field. In fact, given that RPM mixtures are being considered as an alternative to the use of D mixtures and given that in 2024, all VDOT D mixtures will be designed using BMD, RPM mixtures are expected to follow a similar path.
6. *VDOT's Materials Divisions and VDOT's Environmental Division should consider identifying additional opportunities for research and field trials to explore elements not considered in this study. These elements include the evaluation of RPM under full-scale accelerated pavement testing, the use of higher RAP contents (up to 30%) with engineered recycled plastics, the feasibility and process of recycling asphalt mixtures already containing recycled plastic, and LCA and developments of Environmental Product declarations for RPM mixtures.* This will highlight the impact of further recycling on the properties and production of such mixtures, and the potential generation of hazardous emissions into the environment.
7. *VDOT's Materials Division should consider investigating local plastic waste in the Commonwealth and developing guidelines for accepting asphalt mixtures incorporating engineered plastic waste repurposed from the Commonwealth's plastic waste.* All trials conducted in Virginia thus far have involved the use of proprietary products, engineered recycled plastic-based additives, most of which were imported to the Commonwealth. This study will play a vital role in establishing a circular system.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in "Acknowledgments") for the project collaborated to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided in this section.

Implementation

In regard to *Recommendation 1*, VDOT's Central Office Materials Division will collaborate with VDOT's Environmental Division, VDOT Districts, VTRC, and Industry representatives to assemble a group of stakeholders. This group will develop a comprehensive plan and roadmap, outlining the research needed for incorporating recycled plastic into asphalt mixtures and establish a course of action for future implementation. Discussions will also cover the potential addition of plastic-based proprietary products into VDOT's Approved Product List, especially those with completed field trials within the commonwealth. Additionally, topics of interest will include establishing a framework for approving and/or rejecting specific plastic-based additives and products. This work is expected to start in the spring of 2026.

In regard to *Recommendation 2*, VTRC and VDOT personnel in districts where RPM mixtures were placed will monitor the performance of these sections for the next 3–5 years in order to capture a more representative documentation of field performance for this type of paving material. VTRC and VDOT Districts will coordinate with VDOT's Maintenance Division and collect performance data for the sections evaluated in this study annually from VDOT's PMS and share the data with VDOT's Central Office Materials Division and all VDOT Districts. This effort will be documented as part of a technical assistance project or a technical brief.

In regard to *Recommendation 3*, further communication with VDOT districts will involve sharing a documentary video, recently created by VTRC, VDOT Richmond District, Industry, and VDOT Communications Division. The video is available on the official VDOT YouTube page at https://youtu.be/m55FpMprYqo. Two RPM demonstration trials were constructed during the 2022 paving season, and one trial was conducted in 2023. The 2022 trials featured four RPM mixtures with four different recycled plastics alongside two reference unmodified mixtures. The 2023 trial used one RPM mixture. The findings from these trials will be documented as part of the ongoing VTRC Project No. 122604, Sustainable Surface Mixtures Incorporating Recycled Plastic Waste and High RAP Contents.

In regard to *Recommendation 4*, VDOT's Environmental Division and VTRC personnel will initiate research targeted at applying these methods to samples of stormwater runoff and soils to identify any modifications or improvements that are needed and to better understand the environmental fate and transport of the plastics used in RPM asphalts and other DOT applications. This research will begin no later than May 31, 2024. Further research should consider the following points in particular:

- Methods of improving or substituting the analytical techniques used in this study to enable more accurate polymer identification. The literature review found that the use of mass spectrometry in place of or in series with FTIR is effective for this.
- Development of these methods into a well-defined, user-friendly test method for detecting and quantifying microplastics in stormwater and soil samples. This effort should also include the development of method detection limits through rigorous testing.
- A minimum of 2 years of sampling stormwater runoff and soil collected from both P1 and P2 trial sites and other control sites with similar site characteristics such as ADT traffic patterns and surrounding land cover. This length of time is necessary given the typical service life of asphalt pavements.
- Stormwater and soil sampling of other sites where erosion control netting, silt fencing, and/or other plastic materials commonly used during road construction and maintenance have been used. This information will be valuable for the identification of contributing sources of microplastics in field samples. The expansion of the scope to include these materials would also address requests made by the Environmental Research Advisory Committee to investigate sources of microplastics.

In regard to *Recommendations 5 and 7*, VTRC will draft and submit separate RNSs to the appropriate VTRC Pavement Research Advisory Subcommittee by no later than the fall of 2026. This submission will account for the discussions conducted by stakeholders as part of Recommendation 1.

In regard to *Recommendation 6*, VTRC Project No. 122604, Sustainable Surface Mixtures Incorporating Recycled Plastic Waste and High RAP Contents, is ongoing. One of the major objectives of this research is to continue evaluating RPM asphalt mixtures produced during the 2022 and 2023 paving seasons while accounting for a relatively high RAP content. Another objective of the study is to evaluate the feasibility and process of recycling asphalt mixtures already containing recycled plastic waste. Furthermore, VTRC and VDOT were awarded a grant to quantify greener pavements in Virginia in response to the Federal Highway Administration (FHWA) Climate Challenge, with a major focus on quantifying emissions from sustainable pavements. This effort, VTRC Project No. 124057, FHWA Climate Challenge, is ongoing. The objectives of this project are to expand the level of knowledge within VDOT and to begin collecting the necessary data to quantify the environmental impacts of selected paving practices within the agency, including the incorporation of recycled plastics into asphalt mixtures.

Benefits

This project assessed the viability and feasibility of producing asphalt mixtures modified with recycled plastic (plastic waste) in Virginia. Currently, over 76% of the plastic waste in the U.S. is being stacked and landfilled without further repurpose and reuse (Habbouche, 2022; Willis et al., 2020; Yin et al., 2020). Therefore, researchers and engineers started looking at asphalt mixtures as a potentially viable "home" to incorporate some of the recycled plastic waste commodity. This project presented an opportunity to start developing a laboratory performance and fundamental material property database on RPM asphalt mixtures produced with raw materials typically used in Virginia.

Furthermore, given that there are seven types of plastics available in the environment, this project represents the first step among many others that will help VDOT gain gradual knowledge about the type(s) of waste plastic that may be compatible with the paving materials typically used in the Commonwealth. These materials are expected to provide promising long-term performance. The data collection that happened as part of this project and the collection that will occur in future trials will provide a better understanding of the potential environmental impacts associated with the use of recycled plastics in asphalt mixtures. For example, according to the corresponding plastic supplier, the one-night trial of SM-12.5RPM P1 (~700 tons) helped save, on average, the equivalent weight of approximately 635,000 single-use plastic bags going to landfills. This was accompanied by an offset of approximately 10,770 kg of CO_2. Furthermore, according to the corresponding plastic supplier, the one-night trial of SM-12.5RPM P2 (~700 tons) helped recycle and repurpose an average of about 49,560 half-liter water bottles. Although these numbers might seem low due to only one trial being conducted, an increase in using such alternatives can help reduce fossil fuel usage, leading to a reduction in the carbon footprint and fostering a circular economy. Moreover, if used responsibly on low to medium traffic-level routes, RPM mixtures can extend the performance life of pavements by 6 to

9% based on hypothetical preliminary ME simulations.

Implementing Recommendations 1 and 3 will help educate and facilitate discussions and disseminate accurate information to increase the use of RPM asphalt mixtures if needed in Virginia and in a responsible manner. *Implementing Recommendation 2* will assist in assessing the cost-benefit of using RPM mixtures in Virginia.

The benefits of *implementing Recommendation 4* include gaining a better understanding of the potential for RPM asphalts to release microplastics into the environment under real-world conditions. Additionally, evaluating sites where erosion control products containing plastic have been used will enable VDOT to modify existing practices or types of products used to reduce the long-term environmental impact of construction and maintenance projects. This benefit aligns with current VDOT environmental stewardship goals to avoid and compensate for construction and maintenance-related impacts on the environment.

Implementing Recommendations 5 through 7 will contribute to the experience of using truly innovative materials with good performance prospects, major components of which stem from recycling efforts.

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REFERENCES

Abatech, Inc. Rheology Analysis Software, Version 2.0. Blooming Glen, PA, 2022.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards*. Washington, DC, 2017.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards*. Washington, DC, 2018.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards*. Washington, DC, 2019.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards*. Washington, DC, 2020.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards*. Washington, DC, 2021.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, and AASHTO Provisional Standards*. Washington, DC, 2022.

Anderson, R.M., King, G.N., Douglas, H., and Blankenship, P.B. Evaluation of the Relationship Between Asphalt Binder Properties and Non–Load Related Cracking. *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, 2011, pp. 615–649.

Artetxe, M., Lopez, G., Amutio, M., Elordi, G., Olazar, M., Bilbao, J. Operating Conditions for the Pyrolysis of Poly-(ethylene Terephthalate) in a Conical Spouted-Bed Reactor. *American Chemical Society: Industrial Engineering Chemical Research,* Vol. 49, No. 5, 2010, pp. 2064–2069.

ASTM International. *ASTM D4694-20: Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device.* West Conshohocken, PA, 2020.

ASTM International. *ASTM D8360-22, Standard Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using the Ideal Rutting Test*. West Conshohocken, PA, 2022.

ASTM International. ASTM D8225-19, *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. West Conshohocken, PA, 2019.

ASTM International. *ASTM E1845-19: Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.* West Conshohocken, PA, 2015.

Boz, I., Flintsch, G.W., de LEON Izeppi, E. *Functional Characteristics of Dense-Graded Asphalt Surface Mixtures.* VTRC 23-R15. Virginia Transportation Research Council, Charlottesville, 2023a.

Boz, I., Habbouche, J., Diefenderfer, S.D., Coffey, G.P., Ozbulut, O.E., and Seitllary, A. *Simple and Practical Tests for Rutting Evaluation of Asphalt Mixtures in the Balanced Mix Design Process*. VTRC 23-R11. Virginia Transportation Research Council, Charlottesville, 2023b.

California Senate Bill No. 1422. *California Safe Drinking Water Act: microplastics*. 2018. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1422. Accessed August 7, 2023.

California Water Boards. *Definition of Microplastics in Drinking Water*. State Water Resources Control Board, Sacramento, 2020. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html. Accessed August 7, 2023.

Christensen, D.W., and Tran, N. *NCHRP Research Report 982: Relationships Between the Fatigue Properties of Asphalt Binders and the Fatigue Performance of Asphalt Mixtures*. Transportation Research Board, Washington, DC, 2022.

David, J., Steinmetz, Z., Kučerík, J., and Schaumann, G.E. Quantitative Analysis of Poly(ethylene terephthalate) Microplastics in Soil via Thermogravimetry-Mass Spectrometry. *American Chemical Society: Analytical Chemistry*, Vol. 90(15), 2018, pp. 8793–8799.

Diefenderfer, S.D., Boz, I., and Habbouche, J. *Balanced Mix Design for Surface Asphalt Mixtures: 2019 Field Trials.* VTRC 21-R21. Virginia Transportation Research Council, Charlottesville, 2021.

Diefenderfer, S.D., Habbouche, J., and Boz, I. *Balanced Mix Design for Surface Asphalt Mixtures: 2020 Field Trials*. VTRC 23-R13. Virginia Transportation Research Council, Charlottesville, 2023.

Federal Highway Administration. *Cyclic Fatigue Index Parameter (S_{app}) for Asphalt Performance Engineered Mixture Design.* FHWA-HIF-19-091. Federal Highway Administration, Washington, DC, 2019.

Federal Highway Administration. *Delta Tc Binder Specification Parameter.* FHWA-HIF-21-042. Federal Highway Administration Washington, DC, 2021a,

Federal Highway Administration. *Rutting Strain Index (RSI) Parameter for Asphalt Balanced Mixture Design*. FHWA-HRT-21-044. Federal Highway Administration, Washington, DC, 2021b.

Flintsch, G.W., de León, E., McGhee, K., and Al-Qadi, I.L. Pavement Surface Macrotexture Measurement Applications. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1860, 2003, pp. 168–177.

Garcia V., Miramontes, A., Garibay, J., Abdallah, I., and Nazarian, S. *Improved Overlay Tester for Fatigue Cracking Resistance of Asphalt Mixtures.* TxDOT 0-6815-1. University of Texas at El Paso, 2016.

Glover, C.J., Davison, R.R., Domke, C.H., Ruan, Y., Juristyarini, P., Knorr, D.B., and Jung, S.H. *Development of a New Method for Assessing Asphalt Binder Durability With Field Validation.* FHWA/TX-05/1872-2. Texas Transportation Institute, College Station, 2005.

Habbouche, J., Boz, I., Hajj, E.Y., and Morian, N.E. Influence of Aging on Rheology- and Chemistry-Based Properties of High Polymer-Modified Asphalt Binders. *International Journal of Pavement Engineering*, Vol. 23, 2022, pp. 3285–3303.

Habbouche, J. Towards Sustainable Paving Virginia's Initial Efforts to Incorporate Recycled Plastic Waste Into Asphalt Mixtures. *Virginia Asphalt Magazine,* Fall & Winter Issue, 2022, pp. 10–14.

Mansa, R., and Zou, S. Thermogravimetric Analysis of Microplastics: A Mini Review. *Journal of Environmental Advances*, Vol. 5, 2021, No. 100117.

Masura, J., Baker, J., Foster, G., Arthur, C. *Laboratory Methods for the Analysis of Microplastics in the Marine Environment: Recommendations for Quantifying Synthetic Particles in Waters and Sediments.* NOAA Technical Memorandum NOS-OR & R-48. NOAA Marine Debris Division, Silver Spring, MD, 2015.

McGhee, K.H. *Development and Implementation of Pavement Condition Indices for the Virginia Department of Transportation, Phase I: Flexible Pavements*. Virginia Department of Transportation, Materials Division, Richmond, 2002.

Murphy, M. *Microplastics Expert Workshop Report*. United States Environmental Protection Agency, Office of Wetlands, Oceans and Watersheds, Washington, D.C., 2017.

Nel, H.A., Chetwynd, A.J., Kelly, C.A., Stark, C., Valsami-Jones, E., Krause, S., Lynch, I. An Untargeted Thermogravimetric Analysis-Fourier Transform Infrared-Gas Chromatography-Mass Spectrometry Approach for Plastic Polymer Identification. *American Chemical Society: Environmental Science and Technology,* Vol. 55, No. 13, 2021, pp. 8721–8729.

Primpke, S., Christiansen, S.H., Cowger, W., De Frond, H., Deshpande, A., Fischer, M., Holland, E.B., Meyns, M., O'Donnell, B.A., Ossmann, B.E., Pittroff, M., Sarau, G., Scholz-Böttcher, B.M., Wiggin, K.J. Critical Assessment of Analytical Methods for the Harmonized and Cost-Efficient Analysis of Microplastics. *Applied Spectroscopy*, Vol. 74, No. 9, 2020, pp. 1012–1047.

Rada, G.R., Jones, D.J., Harvey, J.T., Senn, K.A., and Thomas, M. *Guide for Conducting Forensic Investigations of Highway Pavements.* NCHRP Report 747.Transportation Research Board, Washington, DC, 2013.

Rosso, B., Corami, F., Vezzaro, L., Biondi, S., Barbara, B., Barbante, C., Gambaro, A. Quantification and Characterization of Additives, Plasticizers, and Small Microplastics (5-100 µm) in Highway Stormwater Runoff. *Journal of Environmental Management*, Vol. 324, No. 116348. 2022.

Rowe, G.M., Sharrock, M.J., Bouldin, M.G., and Dongre, R.N. Advanced Techniques to Develop Asphalt Master Curves From the Bending Beam Rheometer. *Petroleum and Coal*, Vol. 43, 2011, pp. 54–59.

Ruan, Y.H., Davison, R.R., and Glover, C.J. Oxidation and Viscosity Hardening of Polymer-Modified Asphalts. *Energy and Fuels*, Vol. 17, 2003, pp. 991–998.

Safaei, F., and Castorena, C. Temperature Effects of Linear Amplitude Sweep Testing and Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2574, 2016, pp. 92–100.

Schymanski, D., Goldbeck, C., Humpf, H., Fürst, P. Analysis of Microplastics in Water by Micro-Raman Spectroscopy: Release of Plastic Particles from Different Packaging into

Mineral Water. *Water Research*, Vol. 129, 2017, pp. 154-162.

Texas Department of Transportation. *Test Procedure for Overlay Test Tex-248-F. Effective Date: July 2019.* https://ftp.txdot.gov/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit248.pdf. Accessed December 15, 2022.

Thermo Electric Corporation. OMNIC User's Guide, Version 7.3. *Thermo Electric Corporation,* Madison, WI, 2006.

Virginia Department of Transportation. *Road and Bridge Specification*s. Richmond, 2020.

Virginia Test Methods. *VTM-102: Determination of Asphalt Content From Asphalt Paving Mixtures by the Ignition Method*. Virginia Department of Transportation, Richmond, 2013a.

Virginia Test Methods. *VTM-106: Determining Pavement Roughness and Rut Depth Using an Accelerometer Established Inertial Profile Referencing System*. Virginia Department of Transportation, Richmond, 2013b.

Virginia Test Methods. *VTM-120: Method of Test for Measurement of Permeability of Bituminous Paving Mixtures Using a Flexible Wall Permeameter—(Asphalt lab)*. Virginia Department of Transportation, Richmond, 2000.

Von Quintus, H.L., Mallela, J., Bonaquist, R., Schwartz, C.W., and Carvalho, R.L. *NCHRP Report 719: Calibration of Rutting Models for Structural and Mix Design*. Transportation Research Board, Washington, DC, 2012.

Werbowski, L.M., Gilbreath, A.N., Munno, K., Zhu, X., Grbic, J., Wu, T., Sutton, R., Sedlak, M.D., Deshpande, A.D., Rochman, C.M., Urban Stormwater Runoff: A Major Pathway for Anthropogenic Particles, Black Rubbery Fragments, and Other Types of Microplastics to Urban Receiving Waters. *American Chemical Society: Environmental Science and Technology, Water*, Vol. 1(6), 2021, pp. 1420–1428.

Willis, R., Yin, F., and Moraes, R. *Recycled Plastics in Asphalt Part A: State of the Knowledge*. NAPA – IS – 142, National Asphalt Pavement Association, Greenbelt, Maryland, 2020.

Yang, K., Li, R., Castorena, C., and Underwood, B.S. Correlation of Asphalt Binder Linear Viscoelastic (LVE) Parameters and the Ranking Consistency Related to Fatigue Cracking Resistance*. Construction and Building Materials*, Vol. 322, 126450, 2022.

Yin, F., Moraes, R., and Anand, A. *Recycled Plastics in Asphalt Part B: Literature Review*. NAPA – IS – 142, National Asphalt Pavement Association, Greenbelt, Maryland, 2020.

Yu, J., Wang, P., Ni, F., Cizdziel, J., Wu, D., Zhao, Q., Zhou, Y. Characterization of Microplastics in Environment by Thermal Gravimetric Analysis Coupled with Fourier Transform Infrared Spectroscopy. *Journal of Marine Pollution Bulletin*, Vol. 145., 2019, pp. 153–160.

Zhou, Y., Wang, J., Zou, M., Jia, Z., Zhou, S., Li, Y. Microplastics in Soils: A Review of Methods, Occurrence, Fate, Transport, Ecological and Environmental Risks. *Science of the Total Environment*, Vol. 748, 2020, No. 141368.