THE SUSTAINABILITY OF RECYCLED PLASTIC MODIFIED ASPHALT: A LIFE CYCLE ASSESSMENT AND PERFORMANCE BASED APPROACH

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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1. INTRODUCTION

The construction industry and built environment are vital sectors of the global economy, but they have significant, negative impacts on the environment. As it exists currently, the construction and use of the built environment account for 40% of greenhouse gas emissions annually (Crawford, 2022). These emissions are split into two subsets: building energy use (27%) and embodied emissions (13%) (Architecture2030, 2023), the latter of which constitute the emissions that are generated from construction materials and processes. Although recent efforts have been made to improve the sustainability of the built environment through new technologies and environmental regulations, energy consumption and greenhouse gas emissions have continued to rise (Crawford, 2022). Therefore, the construction industry presents a crucial opportunity to reduce global energy consumption and emissions. Of the two subsets of global greenhouse gas emissions coming from the built environment, there has been a stronger focus on reducing building energy use emissions compared to reducing embodied emissions. While this is necessary given that building energy emissions are twice as large as embodied emissions, attention needs to be given to aspects of embodied emissions such as construction methods and materials. This is crucial to ensure that all facets of the construction industry contribute to a sustainable future.

One promising path by which construction materials can be made more sustainable is by incorporating recycled material as a replacement for some virgin materials, diverting materials from waste facilities at their end of life and reducing the greenhouse gas emissions required to produce new construction materials as a result. Widely used construction materials such as concrete, steel, and asphalt pavement have the potential to produce the most benefit in terms of greenhouse gas emissions if they can successfully be made more sustainable. There is a long history of using a diverse variety of additives such as polymers, fibers, and recycled materials in construction materials such as concrete and asphalt pavement. Currently, asphalt pavement is one of the most recycled products in the United States with a range of 15% to 30% of Reclaimed Asphalt Pavement (RAP) being reused in combination with virgin asphalt binders and aggregate to produce new asphalt pavement (Williams et al., 2019). Other recycled materials that have been used with success in improving asphalt pavement are recycled tire rubber and recycled asphalt shingles. The past history of asphalt's ability to provide a novel end-of-life destination for waste materials means that there is similar potential for successfully incorporating other recycled waste, namely recycled plastic waste, into new asphalt pavement. If recycled plastic waste can be successfully incorporated into asphalt pavement, there are potential benefits such as keeping large amounts of plastic out of landfills or sensitive habitats, improving the performance of asphalt roadway, and incentivizing more recycling of plastic. However, before incorporating recycled plastic into asphalt pavement, it must first be determined how it affects the performance and life cycle global warming potential (GWP) of the roadway relative to conventional asphalt roadways.

1.1 Plastic Pollution

The overconsumption of plastic products is one of the world's many unsustainable habits. Plastic production doubled between 2000 and 2019, reaching 460 million tons. The generation of plastic waste has followed a similar trend, more than doubling from 2000 to 2019, reaching 353 million tons. However, only 4% of this plastic is recycled while 73% is sent to landfills (OECD, 2022). The growing trend of single-use plastics utilized in packaging, textiles, and personal protection equipment (PPE) has led to massive accumulation of the short-lived plastic products in the waste stream due to poor waste management, single-use consumption, low price of virgin fossil fuel feedstock relative to bioplastic feedstock. For example, during the Covid-19 pandemic, "the World Health Organization requested a 40% increase in disposable PPE production in view of monthly global consumption and waste of 129 billion face masks and 65 billion gloves; in the case of PPE use in the United States this would mean that an entire year's worth of medical waste would be generated in just two months" (Adyel. 2020). The negative impacts of plastic pollution on human health in the form of microplastics, the imbalance that plastics introduce to ecosystems due to the plastics' inability to decompose organically and biodegrade have led many individuals, organizations, and countries around the world to start thinking about finding alternative solutions that are more sustainable and environmentally conscious (OECD, 2022). The Organization for Economic Co-operation and Development (OECD) estimates that" the current use of plastics is far from circular. Wherein, of the 353 million tons of global plastic waste generated globally in 2019, only an estimated 55 million tons were collected for recycling, 22 million tons of which were disposed" (OECD, 2022). Moreover, the projected world population growth, estimated to reach 9.9 billion by 2050 according to the United States Census Bureau, combined with the increasing trend of globalization of goods and services, has led to a significant rise in the usage and reliance on plastics compared to other synthetic materials such as cement or steel. The current plastic consumption pattern is alarming and its resulting waste that keeps accumulating in landfills is posing a threat to the environment "In the early 2000's, the amount of plastic waste we generated rose more in a single decade than it had in the previous 40 years combined. Today, we produce about 400 million tons of plastic waste every year" (UNEP, 2021).

As the growing economies in OECD countries spur the need for more infrastructure projects and increasing investments in real estate development, the associated plastic waste resulting from various economic sectors is projected to increase as shown in Figure 1 (OECD, 2022). The Chinese government's ban on importing plastic waste in 2018 had a significant impact on the global recycling industry. Many countries such as the United States and Germany used to export their low-grade plastics that were often difficult and expensive to recycle. However, in the aftermath of the ban, these countries are seeking alternative markets for their plastic waste rather than routing this waste to incineration or landfills. The challenges for plastic waste destinations that were created by the Chinese import ban had created new opportunities for innovative reuse in proven resource recovery practices such as asphalt pavement.

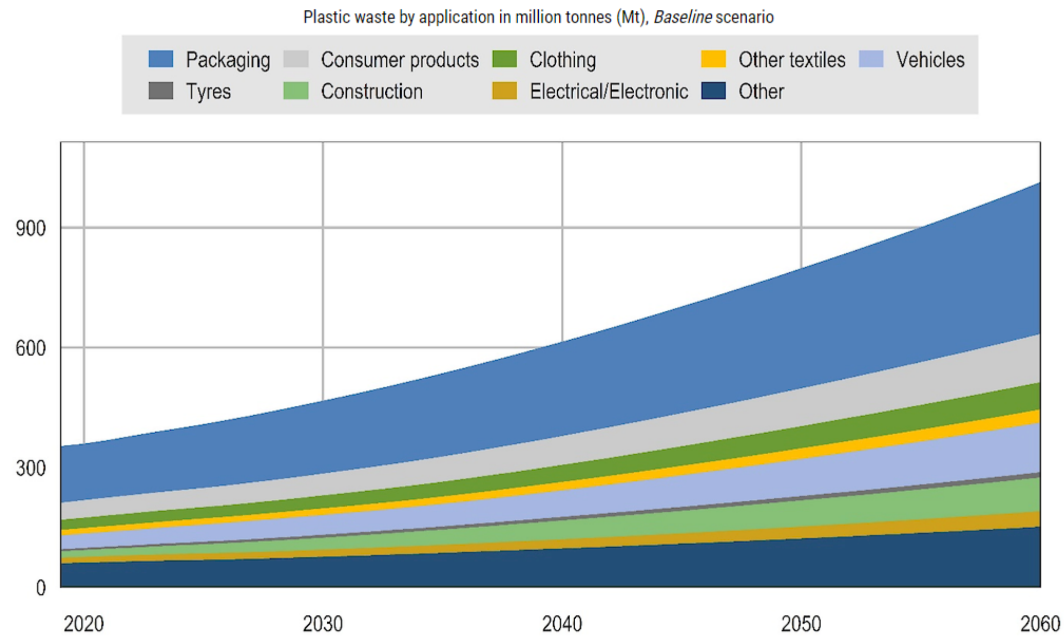


Figure 1: Plastic Waste Generation Projection by Application. (OECD, 2022)

With the Biden administration's Build Back Better infrastructure modernization plan, a number of legislative proposals have been introduced that emphasize the importance of pavement sustainability. For example, the Accelerated Research on the Potential for Recycling Plastics in Asphalt act seeks to evaluate the effects of Recycled Plastic Modified (RPM) asphalt mixtures on long-term pavement performance (NAPA, 2020). The increased focus on sustainability in infrastructure development is intertwined with the renewed interest in RPM asphalt mixtures as a viable solution for reducing plastic waste and shift towards a circular economy.

1.2 Life Cycle Assessment (LCA)

Life-cycle assessment (LCA) is a technique that can be used to evaluate the environmental impact of a product, process, or system by examining all the inputs and outputs over the life cycle, from raw material production to end of life phases. This systematic approach identifies where the most relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs . It gives agencies the ability to investigate areas where they can improve (FHWA, 2016). LCA frameworks were developed in the 1990s with the rise of green construction regulations and sustainability policies that incurred the need for many companies and institutions to support carbon storage of their products via the LCA approach. In light of deteriorating infrastructure and accumulating maintenance costs, the use of LCA in decision making methodology is becoming integral to the overall macroeconomic aspect of the construction industry. The LCA phases can help break down the products' environmental impacts, energy usage, and carbon footprint. These phases are shown in Figure 2 below.

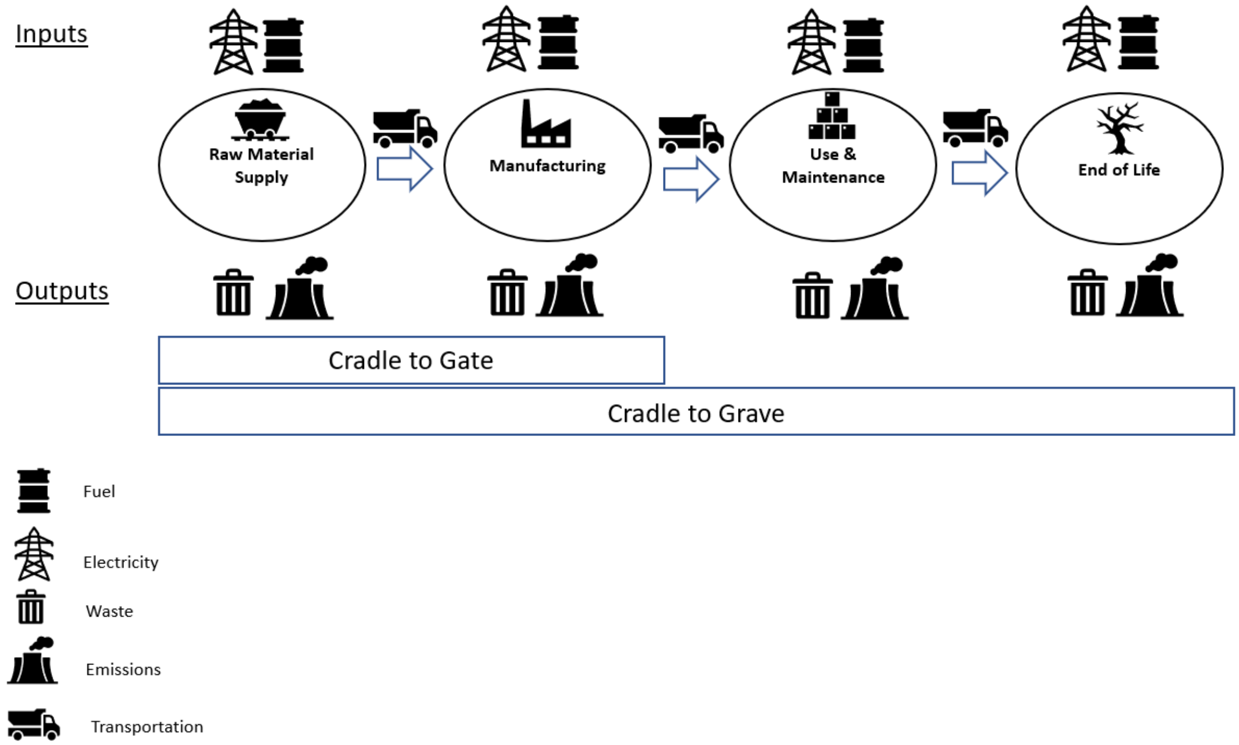


Figure 2. Basic LCA Phase Diagram

A key design consideration in conduction of an LCA study is the choice of a functional unit (FU), which is the quantifiable measure of the performance of a product or process. The functional unit is critical for comparing the relative characteristics of different products, identifying potential areas for improvements, and highlighting potential trade-offs. The functional unit definition also determines the LCA system boundaries and standardizes the comparison framework for performance criteria such as global warming potential (GWP) declared functional unit of each product.

1.3 Review of Literature

According to the National Asphalt Pavement Association (NAPA) publications, there are various successful methods for recycling asphalt with additive recycled material via the dry process or wet process. The NAPA *state of knowledge* publications included about 115 research papers from various countries including the United States, Australia, India, China, and Canada. Based on these research papers and peer-reviewed journal articles, the most researched plastic types were polyethylene (PE) both high-density (HDPE) and low-density (LDPE), in addition to polyethylene terephthalate (PET) due to their abundance in the waste stream, specific gravity, melting temperature, particle size, and safe operating conditions in laboratory and field environments compared to other plastic types such as polyvinyl chloride (PVC). However, there are some knowledge gaps in terms of systematic processing methods when recycling different plastic types which may introduce contaminants into the asphalt mixture and affect the RPM asphalt mix performance properties (Yin et al., 2020).

1.3.1 Performance of Recycled Plastic Modified Asphalt

Past research on the impact of incorporating recycled plastic into asphalt pavement has mainly focused on laboratory testing of RPM asphalt samples. The plastics most commonly used in these assessments were HDPE and LDPE. The studies have evaluated the impact of recycled plastics on asphalt binder and aggregate performance in terms of stiffness and rutting resistance. It was consistently found that adding recycled plastics to asphalt mixtures increased their stiffness which led to improved resistance to permanent deformation. However, conclusions about the fatigue and cracking resistance of RPM asphalt mixtures were inconsistent across different studies. In addition, RPM asphalt mixtures required extra attention to maintain specific temperatures during the construction phase to ensure that the asphalt could be compacted in the field before the plastics recrystallized (NAPA, 2020).

Documented field performance of RPM asphalt mixtures has been limited when compared to laboratory assessments. Recently, numerous demonstration projects of RPM asphalt mixtures have been constructed in several countries, including the United States. For example, the Virginia Department of Transportation (VDOT) conducted a study in Chesterfield County, Virginia, where the Virginia Transportation Research Council (VTRC), the research division of VDOT, designed four asphalt mixtures and placed them as surface mixtures on a section of secondary roadway (Figure 3).

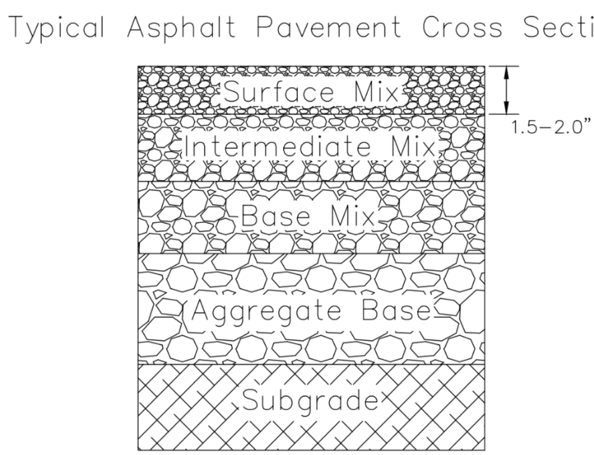


Figure 3. Typical Asphalt Pavement Cross Section

The VTRC field study project aims to "document and evaluate the constructability, laboratory performance and initial field performance of RPM asphalt mixtures produced using plastic waste and typical raw materials in terms of aggregates and asphalt binders compared alongside with VDOT typical control mixes" (VTRC, 2023). There are two control asphalt mixtures, one for use on secondary roadways and one for use on interstates, and two RPM asphalt mixtures with varying compositions and types of recycled plastic. The road sections (shown in Figure 4) were paved with the four asphalt mixtures during the 2021-construction season, and are continuously monitored to observe differences in performance across conventional and RPM asphalt mixtures.

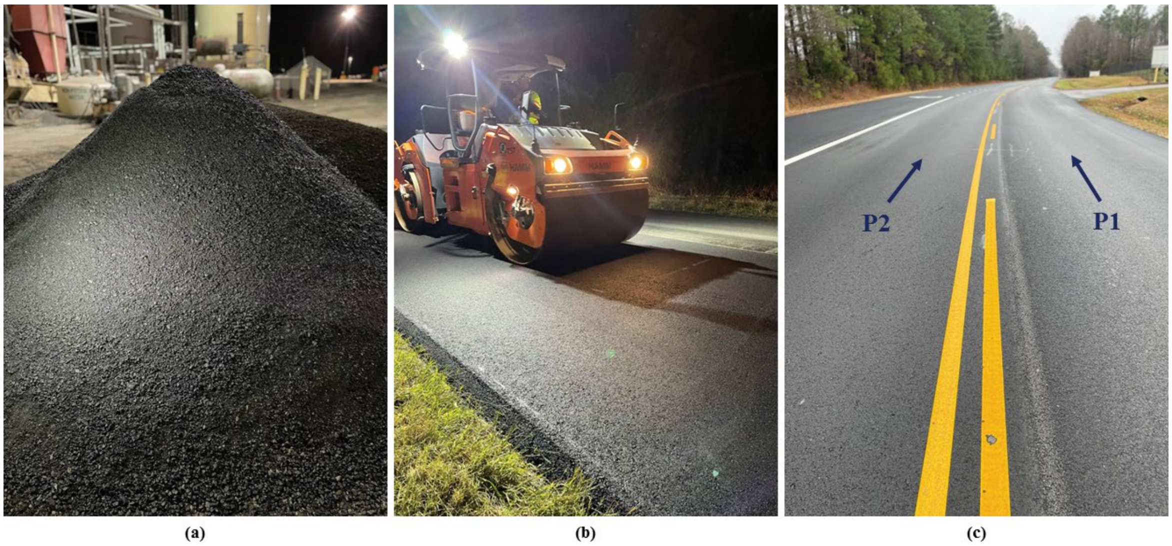


Figure 4. (a) Loose RPM Asphalt Mixtures, (b) RPM Pavement Being Compacted, (c) RPM Pavements in-Service 4 Months After Placement on Old Stage Road in Chesterfield County, Virginia. (Virginia Asphalt Association, 2022)

1.3.2 Life Cycle Assessment (LCA) of Recycled Plastic Modified Asphalt

There has been some previous LCA-based assessment of RPM asphalt paving materials, most notably by Rangelov et al. (2021) and Mukherjee et al. (2016). Results from both analyses highlighted the potential value of RPM asphalts; however, each study had several key limitations. In the case of the Rangelov et al. LCA assessment, there was an assumption that the asphalt mixtures containing recycled plastic would have the same service life as conventional asphalt mix, which meant that their study could not articulate how durability differences between conventional and RPM asphalts influenced their relative use phase impacts. Also, Rangelov's LCA focused on one inclusion method (wet process) of one specific plastic type, polyethylene terephthalate (PET) (plastic #1), but did not address other kinds of highly recycled plastic types (high density polyethylene (HDPE) (plastic #2), low density polyethylene (LDPE) (plastic #4), polypropylene (plastic# 5) etc.)

2. OBJECTIVE AND SCOPE

The purpose of this capstone project is to assess both the performance capabilities and the environmental and economic sustainability of RPM asphalt mixtures. This will be accomplished through the following steps:

- Creating control and RPM asphalt mixture samples and testing them in both laboratory and field environments;
- Using existing commercial software to assess the lifespan of various control and RPM mixture designs;
- Conducting an LCA to compare the environmental impacts of different mix designs and draw conclusions about the sustainability of incorporating recycled plastic in asphalt mixtures.

3. METHODS

This section has been divided into two parts to discuss the *experimental methods* used to test and evaluate the performance of RPM asphalt mixtures, as well as the *systems analyses* (LCA) approach used to compare conventional HMA and the experimental RPM mixtures.

3.1 Experimental Evaluation of the Performance of Recycled Plastic Modified Asphalt

The specimens used in the experimental portion of this study were constituted, compacted and tested by VTRC for their ongoing field study mentioned above in section *1.3.1*. There were four asphalt types: two control asphalt mixes, referred to herein as C1 and C2, and two RPM asphalt mixes, referred to herein as P1 and P2. These test specimens were designed in accordance with VDOT specifications for aggregate gradation and volumetric properties. Extensive laboratory tests were performed on the specimens and are described in this section.

3.1.1 Mixtures and Specimens

The four asphalt surface mixtures (SM) tested at VTRC were the two control mixes, C1 and C2 (SM-D and SM-E), and the two RPM asphalt mixes, P1 and P2 (SM-RPM). The first control mixture, C1 (SM-12.5 D), is a mixture typically used on secondary roads. The second control mixture, C2 (SM-12.5 E), is used on heavily trafficked roads such as primary roads and interstate highways. The first RPM mixture, P1 (SM-12.5 P1), uses polyethylene- (HDPE and LDPE) based polymers designed for the enhancement of asphalt binder properties in asphalt surface mixes. The second RPM mixture, P2 (SM-12.5 P2), uses PET-based elastomeric polymers designed to improve the overall performance of asphalt mixtures. All mixtures contain a standard binder type, PG-64S-22, except for Mixture C2 which uses an elastomeric-modified binder, PG-64E-22. Each of these mixtures also contains a percentage of RAP: 30% RAP in Mixture C1 and 15% RAP in Mixtures C2, P1, and P2. These mixtures are listed below in Table 1.

Table 1. Mixture Design Components of Asphalt Samples

Mix Type	SM-12.5D	SM-12.5E	SM-12.5-P1	SM-12.5-P2
Mixture ID	**C1**	**C2**	**P1**	**P2**
RAP Content, %	30	15	15	15
Asphalt Binder ID	PG-64S-22	PG-64E-22	PG-64S-22	PG-64S-22
Plastic Type(s)	N/A	N/A	2 & 4	1
Plastic Content, %	N/A	N/A	5	3

*Plastic Content, % is given as a percent by binder weight. N/A = not applicable.

3.1.2 Asphalt Mixture Testing

Several tests were conducted at VTRC to assess the material and mechanical properties of the selected mixtures. There were three categories of laboratory tests: basic, intermediate, and advanced. For the purpose of this study, intermediate and advanced testing were grouped together. Basic testing is characterized by tests that require a short time for specimen preparation and do not require any specific cutting, coring, or gluing. Basic tests for this study included Cantabro test and indirect tensile cracking test (IDT-CT). Intermediate and advanced testing encompass tests that require cutting, coring, and/or gluing and multiple days to complete and analyze the test results. Intermediate and advanced tests for this study included asphalt pavement analyzer (APA), dynamic modulus |E*|, direct tension cyclic fatigue, and stress sweep rutting (SSR) tests. Once the results of these tests were analyzed, the obtained data was used to simulate the lifespan of each of the asphalt mixtures via FlexMat and FlexPAVE^{TM} software.

3.1.2.1 Basic Testing

Volumetric Properties and Aggregate Gradations of Mixtures

The theoretical maximum specific gravity of each mixture was determined in accordance with AASHTO T 209, *Standard Method of Test for Theoretical Maximum Specific Gravity (Gmm) and Density of Asphalt Mixtures* (AASHTO, 2019). The asphalt binder content of each mixture was determined by the ignition method in accordance with AASHTO T 308, *Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method* (AASHTO, 2018), and Virginia Test Method (VTM) 102, *Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method* (VDOT, 2013). 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, 2019), and AASHTO T 27, *Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates* (AASHTO, 2019). Loose mixtures were conditioned at the compaction temperature and then compacted to N_{design} gyrations using a Superpave gyratory compactor (SGC) in accordance with AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design* (AASHTO, 2017). Basic physical characteristics and volumetric parameters in terms of bulk specific gravity (Gmb), voids in total mixture, voids in mineral aggregate, voids filled with asphalt, fines to aggregate ratio, aggregate effective specific gravity, aggregate bulk specific gravity, absorbed asphalt binder content, effective asphalt binder content, and effective film thickness were determined (Habbouche et al., 2021).

Cantabro Mass Loss Test

The Cantabro mass loss test was used to evaluate the durability of asphalt mixtures in accordance with AASHTO TP 108, *Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens* (AASHTO, 2018). Cantabro test specimens were compacted from loose mixture collected at the plant during production to N_{design} gyrations using a SGC. The Cantabro test specimens were 150 mm in diameter by 115 ± 5mm in height. The Cantabro test was performed by placing the specimens into an uncharged Los Angeles abrasion machine and rotating it for 300 rotations at approximately 30 rotations per minute. Three specimens were tested for each mixture and an average mass loss was determined (Habbouche et al., 2021).

Indirect Tensile Cracking Test (IDT-CT)

IDT-CT was conducted at 25ºC on specimens prepared from loose mixture collected during construction in accordance with ASTM D8225-19 (ASTM, 2019). Tests were performed at a loading rate of 50 ± 2 mm/min on specimens 150 mm in diameter by 62 mm in height compacted with an SGC. The cracking tolerance index (CT_{index}) was then calculated from the load-displacement curve of the test. VDOT is currently evaluating the use of the CT_{index} and a threshold of a minimum CT_{index} of 70 to assess the cracking resistance of asphalt surface mixes subjected to a relatively medium and lower traffic levels (Habbouche et al., 2021).

3.1.2.2 Intermediate and Advanced Testing

Asphalt Pavement Analyzer (APA) Rut Test

The APA is a thermostatic device used to test the rutting susceptibility of asphalt mixtures by applying loading via rubber-lined wheels at different repetitive rates to simulate the stop-go traffic conditions on the surface pavement. The test follows AASHTO T 340, *Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)* standard method at the testing temperature of 64° C over 8000 cycles (AASHTO, 2019). The specimens, 150±2 mm in diameter, were compacted using a SGC to a height of 75±2 mm and an air void level of 7.0±0.5%. VDOT is currently evaluating the use of the APA Rut Depth and a threshold of a maximum rut depth of 8.0 mm to assess the rutting resistance of asphalt surface mixes subjected to relatively medium and lower traffic levels.

Dynamic Modulus Test |E|*

The dynamic modulus of specimens was determined using the Asphalt Mixture Performance Tester (AMPT) with a 25 to 100 kN loading capacity in accordance with AASHTO T 378, *Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA)* (AASHTO, 2019). Tests were performed on specimens 100 mm in diameter by 150 mm in height cored from the center of specimens 150 mm in diameter by 175 mm in height compacted using an SGC. Three testing temperatures (4, 20, and 40°C) and four testing frequencies ranging from 0.01 to 10 Hz were used. Tests were conducted from lowest to highest temperature, and for each test temperature, the tests were conducted from highest to lowest frequency. The tests at each temperature-frequency combination for each mixture were repeated three times (Habbouche et al., 2021).

Direct Tension Cyclic Fatigue Test

The direct tension cyclic fatigue test was performed using the AMPT 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, 2018). The test was performed on specimens 100 m in diameter by 130 mm in height cored from samples 150 mm in diameter by 175 mm in height. All test specimens were compacted to 7.0±0.5% in-place air voids. The developed damage characteristic curves were then used with viscoelastic material properties to obtain the fatigue behavior of the asphalt mixtures. To define the asphalt mixtures' fatigue performance, a fatigue cracking index parameter, referred to as apparent damage capacity (S_{app}), is used (Habbouche et al., 2021). S_{app} was calculated with FlexMAT for Cracking, an Excel-based tool provided by the Federal Highway Administration (FHWA) (FHWA, 2019).

Stress Sweep Rutting Test

The stress sweep rutting test uses the AMPT to characterize the rutting resistance of asphalt mixtures via the shift model at two temperature extremes, high and low. The shift model is based on the permanent deformation behavior of an asphalt mixture in the primary and secondary regions. The test is conducted at two temperature extremes, high and low under a constant applied pressure of 69 kPa with a loading time duration of 0.4 seconds followed by 3.6 seconds resting periods in the case of high temperature and 1.6 seconds resting period in case of low temperature for each cycle. Using advanced analysis software FlexMAT provided by FHWA, the deformation behavior in terms of Rutting Strain Index (RSI) under the strain-rest loading cycles is simulated and calculated for a given location. The test specimens are 100 mm diameter by 150 mm height and were subjected to deviator stress of 100,70, and 130 psi for high temperature test run and 70, 100, 130 psi for low temperature test run (Habbouche et al., 2021). RSI data was collected and implemented into FlexMAT analysis software. Typically, higher RSI accounts for the varied distribution of loading time and temperature throughout the test simulation means a more rutting susceptible mixture.

3.1.3 FlexPAVE™ Mechanistic Software Simulation

FlexPAVE™ is an analysis tool provided by FHWA that can simulate how an asphalt pavement roadway with a specified cross section will perform over a set lifespan using historic climatic data. For the purpose of this analysis, five different roadway cross sections were considered. These sections are displayed in Figure 5 as: D-Section, E-Section, Low Volume-Section, Experimental l-Section (Exp1-Section), and Experimental 2-Section (Exp2-Section).

The D-section is the most encountered section that is typically used on secondary roadways. The E-section is the most encountered section that is typically used on high-volume primary roads and interstate highways. The Low Volume-Section is representative of typical sections for local roadways (such as those in subdivisions). The two experimental roadway cross sections are not typically constructed in practice and are rather considered to perform accelerated tests on the performance of asphalt pavement in-field. Assumed design life for all cross sections was 30 years.

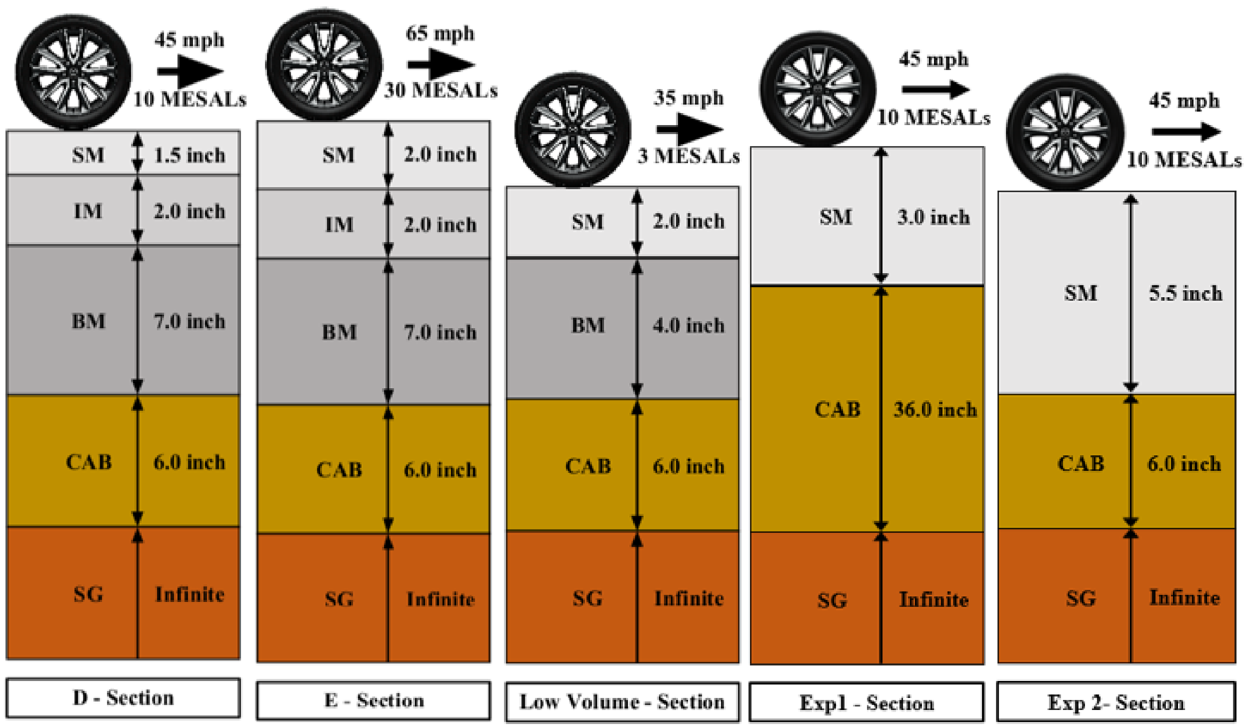


Figure 5. Asphalt Roadway Cross-sections Used in Analysis

These five sections consist of varying depths of some or all of the following layers: surface mix (SM), intermediate mix (IM), base mix (BM), crushed aggregate base (CAB), and subgrade (SG). The surface mix is the only mix that is changed to reflect the four asphalt mixtures evaluated for our project (C1, C2, P1, and P2). Each section is subjected to a certain traffic loading in terms of million equivalent single axle loading (MESAL) and design speed. FlexPAVE^{TM} predicts the cracking and rutting performance for each of the sections over the analysis duration. As this project focuses on the four designed mixtures, the evaluation of their performance was based on two main factors: top-down cracking from the surface layer of the pavement section (except with the experimental sections, which consider both top-down and bottom-up cracking) and the rutting of the surface layer. To assess the performance of the mixtures, the data output from FlexMAT software was used as the input data for FlexPAVE^{TM}, with input parameters defined in terms of location (Chester, Virginia), traffic (MESALs), and climate data. Given that VDOT experiences more concerns with pavement cracking than rutting, the cracking (percent damage) curves are used as the sole criterion for determining the lifespan of each asphalt mixture.

The specified percent damage curves for each pavement section were used to determine the maintenance interval for the four evaluated asphalt surface mixtures. Mixture C1 was taken as the comparator for the D-Section, Low Volume-Section, and the Experimental Sections. Mixture C2 was taken as the comparator for the E-Section since it is the mixture typically used as the surface layer on this exact pavement cross section. The lifespan of the comparator was set at ten years, because VDOT typically replaces asphalt roadway surface mixtures (mill and fill maintenance) on an eight-to-twelve-year schedule. The amount of damage exhibited by the comparator mix at the ten-year timeframe was determined from the damage curves. The maintenance interval for all other mixtures was determined by interpolating to find what number of years corresponded to the same amount of damage as the comparator at the ten-year threshold, and its corresponding percent damage was determined. These values were then used to compute what number of maintenance intervals would be required for each kind of asphalt mixture to deliver the 30-year design life.

3.2 Life Cycle Assessment (LCA)

3.2.1 Overview

An LCA framework was used to compare the selected asphalt mixtures with and without pre-consumer recycled plastic. The FU for the comparison was one lane-mile of roadway section of the surface layer over a 30 year service life. Systems boundaries included raw materials extraction (RME) [A1], manufacturing (mixing [A3] and placement [A5]), service life [B], and end-of-life [C] (Figure 6). Transportation was not considered as a factor in determining the GWP for each mixture as it was assumed that the transport of raw materials to the production site as well as transport of the asphalt mixture to the construction site would be the same for mixtures with and without plastic, given that the production and construction sites are equivalent for all mixes. The key output computed by the LCA model was GWP in units of kg CO_2-equivalent (kg CO_2eq) per FU. The initial modeling framework was based on a previous LCA study by Rangelov et al. (2021) with adaptations to reflect specific mixes used in this study and more detailed articulation of the asphalt use phase (service life). More detail about specific modeling approaches for each life cycle stage is summarized in the following subsections.

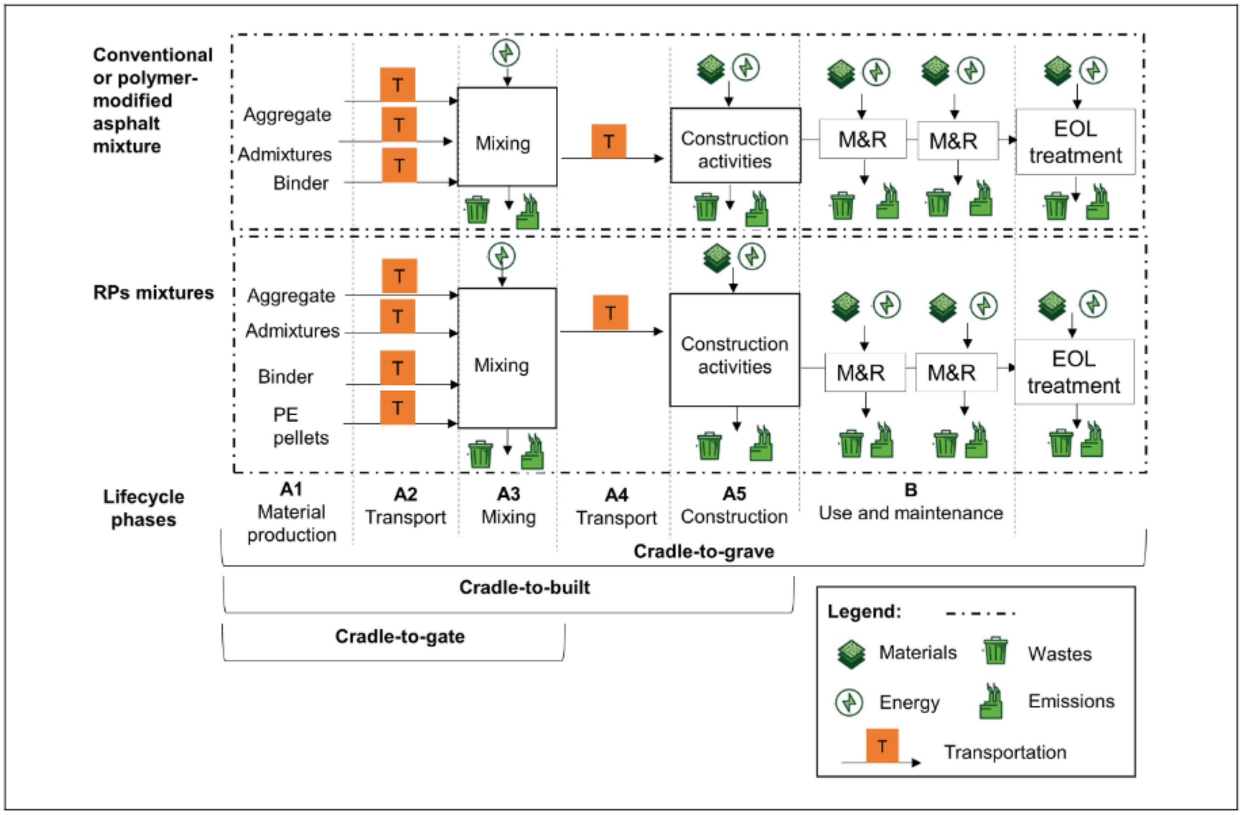


Figure 6. Compared Product Systems: 1 lane-mile of pavement construction with conventional HMA, RPM asphalt, and SBS-modified asphalt (after Rangelov et al (2021)).

The evaluated life cycle phases were as follows: [A1], sourcing of raw materials; [A3], asphalt mixing and manufacturing; [A5], asphalt placement and compaction; [B], use phase and maintenance and rehabilitation (M&R); and [C] end of life treatment.

3.2.1 Raw Materials Supply (RMS) [A1]

GWP impacts arising from raw material supply (RMS) [A1] to produce the materials required to formulate each asphalt mixture were computed using an open-access excel-based software analysis tool called LCAPave, which was provided by the Federal Highway Administration (FHWA, 2021). This approach is consistent with how Rangelov et al. (2021) computed the RMS GWP for the mixes evaluated in their study. The quantities of materials required to produce each mix were computed based on Table 2 and entered into LCAPave in units of MJ per short ton of asphalt mix. GWP estimates from the tool's data library were used without modification for aggregates, binder, and recycled asphalt pavement (RAP). GWP estimates for virgin and recycled plastic were collected from the Franklin Associates report on life cycle impacts for postconsumer recycled resins: PET, HDPE, and PP. These impact factors were manually added into the software's materials library. LCAPave was then used to compute estimates of RMS GWP for all mixes of interest, in units of kgCO_2 eq./short ton. These values were converted to GWP/FU by accounting for the mass of asphalt required to pave the surface layer for one-mile sections of roadways comprising each of the cross sections shown in Figure 5. The difference in RMS for an asphalt surface mixture (C1, C2, P1, or P2) across the five different asphalt roadway cross sections is a function of surface layer thickness. Since the LCA emphasis is on the surface layer, the measure type used for modeling can be in units of mass, density, or volume which can be assumed to deliver the desired functional unit (FU) in short tons.

Table 2. LCAPave Compositions of Asphalt Surface Mixtures

Components	GWP (kg CO_2eq/ton)	Mixture ID (% by mass, ton/ton)			
		Control 1 SM-12.5D	Control 2 SM-12.5 E	RPM Plastic 1 SM-12.5 (P1)	RPM Plastic 2 SM-12.5 (P2)
Coarse Aggregate	2.06	0.3756	0.3570	0.3540	0.3569
Fine Aggregate	4.2	0.2817	0.4416	0.4379	0.4415
RAP (including RAP binder)	1.3	0.3000	0.15	0.15	0.15
Virgin Binder	578	0.0492	N/A	0.0573	0.0508
Virgin Binder (SBS-modified)	694	N/A	0.0524	N/A	N/A
Plastic HDPE	0.56	N/A	N/A	0.0030	N/A
Plastic PET	0.91	N/A	N/A	N/A	0.0018

3.2.2 Manufacturing [A3]

An estimate of manufacturing GWP was computed by adding together emissions from heating and mixing. Regarding heating, the four mixtures require different mixing temperatures which correlates with different amounts of heating oil consumption (D'Angelo, 2008). The mixing temperature for the asphalt mixtures C1, C2, P1, and P2 are given in Table 3. The amount of mixing electricity required to produce the various mixes was calculated based on multiple reports (Mukherjee et al, 2016; Rangelov et al., 2021; Butt et al., 2016). A baseline was obtained from Mukherhee et al. and used for the conventional asphalt mixtures. This value was multiplied by 1.085 to account for an 8.5% increase in mixing duration for RPM asphalts. Another separate value for mixing energy to produce asphalt mixtures containing recycled plastic was collected from Butt et al. (2016). These two values were averaged to estimate the mixing electricity for RPM asphalt mixtures in kWh/ton. GWP impacts for US grid electricity and conventional heating oil were collected from GREET (USDOE, 2022).

Table 3. Mixing Temperatures of Asphalt Mixes

Mix Type	**SM-12.5D**	**SM-12.5E**	**SM-12.5-P1**	**SM-12.5-P2**
Mixture ID	**C1**	**C2**	**P1**	**P2**
Mixing Temperature, ° F	290	320	320	320

3.2.3 Construction [A5]

The construction phase GWP impacts were computed based on estimated emissions arising from initial pavement placement. These estimates were computed by using the mean quantities of diesel fuel required to operate the hauling and placement equipment required to place as much asphalt pavement as is consumed to deliver 1 FU. Equipment usage and fuel consumption were taken from the National Cooperative Highway Research Program (NCHRP) Report 744 (Oman et al., 2013). The asphalt mass placement per FU was multiplied by the site equipment's fuel consumption at a rate of gallon per ton which was then multiplied by the placement's GWP in terms of kg CO_2 eq per functional unit. Fuel GWP impacts were taken from GREET (USDOE, 2022).

3.2.4 Use and Maintenance Phase [B]

GWP impacts arising from pavement removal during maintenance were computed based on data from NCHRP Report 744, including typical milling production rate, vehicle usage, and fuel consumption (Oman et al., 2013). For the maintenance or replacement interval, the assumed total milling time does not differentiate between the conventional and the RPM mixtures. In the replacement calculation, the assumed volume in cubic yards of the roadway was divided by milling removal rate of cubic yards per hour. The sum of the milling equipment fuel consumption of both gasoline and diesel in gallons per hour was multiplied by the total milling time in hours per FU. Finally, the total GWP calculation takes into account the number of repavings required per functional unit over the GWP summation of removal, production of new pavement, and the construction of new pavement. The hauling of used pavement to the processing facility is described in Phase [C] below.

3.2.5 End of Life Treatment [C]

The end-of-life treatment of the asphalt pavement surface layer involved milling and transportation to a landfill facility. The milling calculations for the surface layer of asphalt pavement were reused from the use and maintenance phase [B] as described above. A transport distance to the end-of-life facility of the milled asphalt pavement was assumed to be 30 miles (Rangelov et al., 2021). The GWP was then determined based on the diesel fuel consumption of the dump trucks required to transport the volume of milled asphalt pavement to the landfill. The total GWP for the end of life treatment was determined as the final milling of the surface layer (meaning it does not include the millings calculated based on the asphalt mixture lifespan in Phase [B]) and the GWP from transport for each of the millings that occur, both in Phases [B] and [C].

4. RESULTS AND DISCUSSION

This section is divided into two parts to present and discuss the results of two main aspects of the study: the performance testing of the asphalt mixtures and the LCA results

4.1 Asphalt Mixture Testing

The objective of the asphalt mixture laboratory tests was to evaluate and compare the performance properties of the four evaluated asphalt mixtures: C1, C2, P1, and P2. For the purpose of this study, this testing was focused on the performance of the asphalt binder and aggregate simultaneously.

4.1.1 Basic Testing

Volumetric Properties and Aggregate Gradation of Mixtures

The volumetric properties and aggregate gradations for all evaluated asphalt mixtures are shown below in Table 4 and Figure 7, respectively. The samples of all asphalt mixtures met VDOT standards for volumetric properties and aggregate gradation. However, there was one outlier in the asphalt binder content of mixture P1, which was significantly higher than the other asphalt mixtures at around 6%. This was attributed to a production error in which the recycled plastic was added in addition to the 6% asphalt binder content instead of replacing a percentage of the binder.

Table 4. Volumetric Properties for Evaluated HMA and RPM Mixtures

Mix Type	**SM-12.5D**	**SM-12.5E**	**SM-12.5-P1**	**SM-12.5-P2**
Mixture ID	**C1**	**C2**	**P1**	**P2**
Composition				
RAP Content, %	30	15	15	15
Asphalt Binder ID	PG-64S-22	PG-64E-22	PG-64S-22	PG-64S-22
Property				
N_{design}, gyrations	50	50	50	50
NMAS, mm	12.5	12.5	12.5	12.5
Asphalt Content, %	6.10	6.04	6.83	6.06
Rice SG (G_{mm})	2.504	2.500	2.463	2.506
VTM, %	2.2	2.4	1.9	2.5
VMA, %	16.0	15.4	16.6	15.6
VFA, %	86.0	84.3	88.4	83.9
FA Ratio	1.12	1.21	0.98	1.25
Mixture Bulk SG (G_{mb})	2.448	2.439	2.415	2.442
Aggregate Effective SG (G_{se})	2.761	2.752	2.742	2.761
Aggregate Bulk SG (G_{sb})	2.736	2.708	2.698	2.720
Absorbed Asphalt Content (P_{ba}), %	0.34	0.61	0.68	0.56
Effective Asphalt Content (P_{be}), %	5.78	5.47	6.26	5.53
Effective Film Thickness (F_{be}), µm	10.1	9.2	11.7	8.8

Voids in total mix (VTM), Voids in mineral aggregate (VMA), Voids filled with Asphalt (VFA), Fines/Asphalt ratio (F/A).

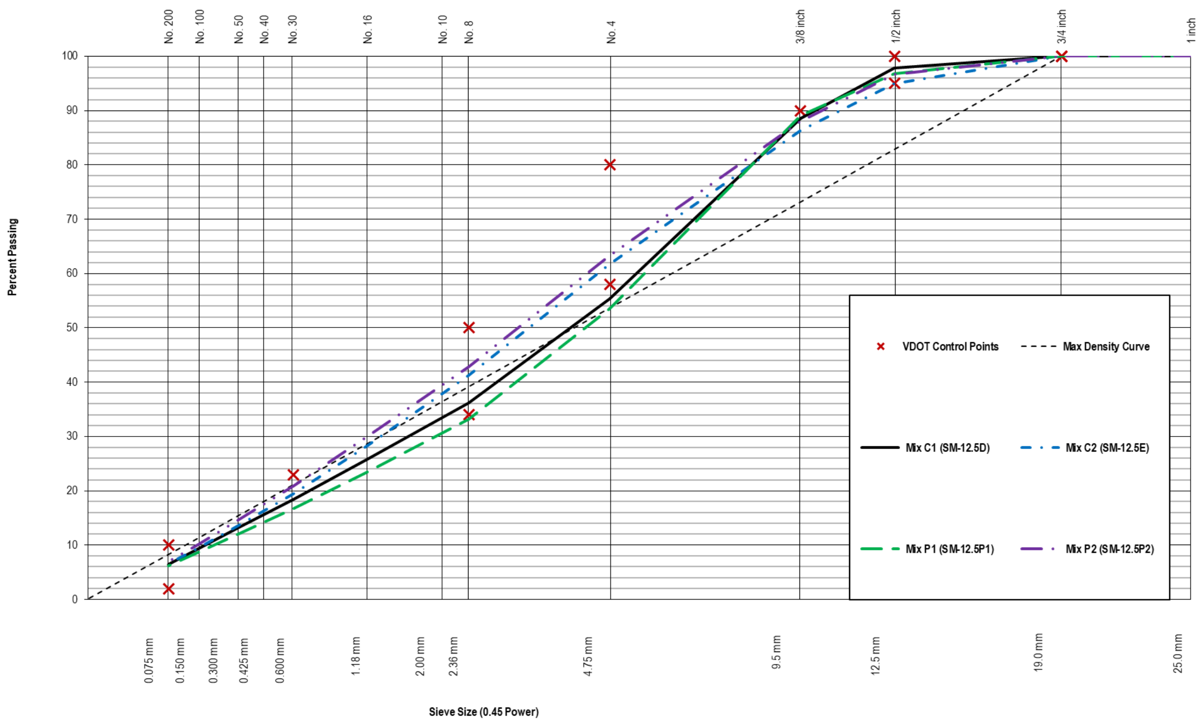


Figure 7. Aggregate Gradation of Asphalt Mixture Samples.

Cantabro Mass Loss Test

The results of the Cantabro mass loss are shown in Figure 8. The mean mass loss ranged from 5.4% to 8.1%, with an average coefficient of variation (COV) of 6.7%. Between the two control mixtures, C2 had a lower mass loss than C1. This is due to the use of SBS modified binder in Mixture C2, therefore indicating that the addition of SBS polymers results in a more durable asphalt mixture. P1 has the lowest average mass loss (5.4%) and is therefore expected to be the most durable mixture. As seen in the figure, Mixtures C1 and P2 had the same and relatively highest mass loss (8.1%). Based on the results, it can be concluded that the type of recycled plastic employed has a large impact on the durability of the corresponding mixture.

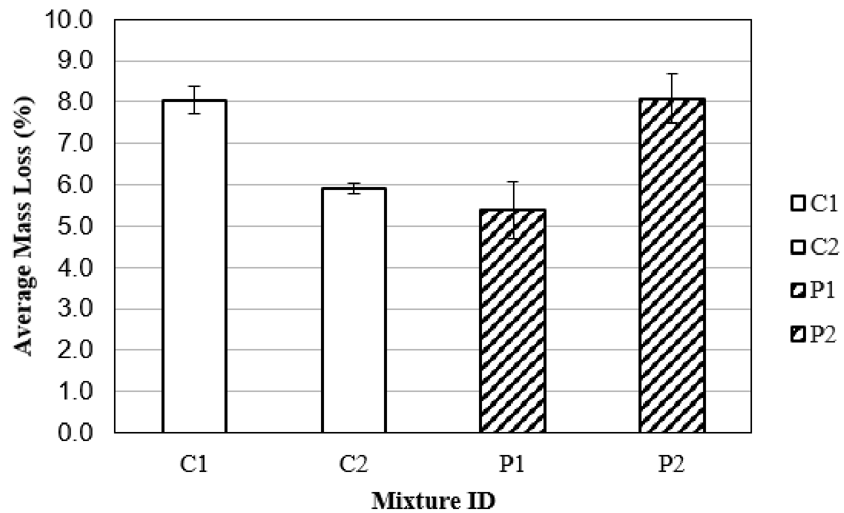


Figure 8. Performance Test Data By Means of for Cantabro Mass Loss Test for All Evaluated Mixtures.

Indirect Tensile Cracking Test (IDT-CT)

Figure 9 shows the CT index values for the four asphalt mixtures as determined by IDT-CT. The CT index is a measure of cracking resistance, and a higher CT index indicates a higher resistance to cracking. However, the results of this test could be highly influenced by the stiffness of the asphalt mixture rather than its true performance in terms of resistance to cracking. The two control mixtures, C1 and C2 have similar CT index values. This could indicate that the IDT-CT is not sensitive to the SBS-modified elastomeric polymer binder used in Mixture C2. Mixture P1 exhibits the highest resistance to cracking, which is expected since it contains the highest percentage of plastic and is therefore the stiffest mixture. Mixture P2 has the lowest CT index due to a lower percentage and different types of plastic incorporated into the mixture.

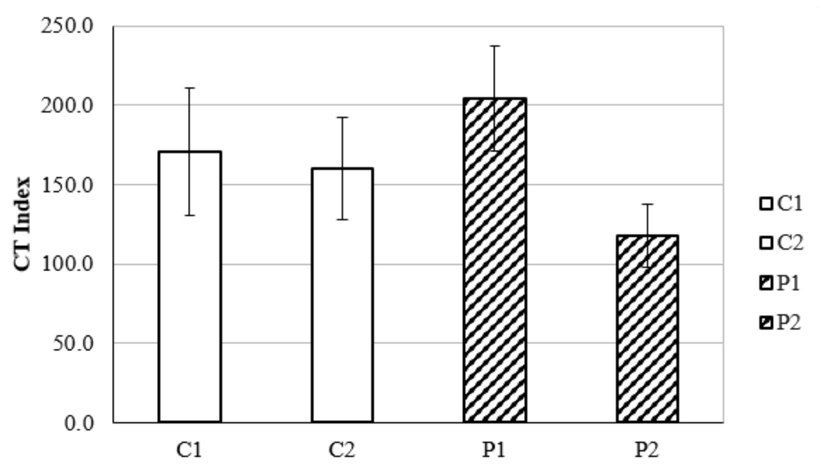


Figure 9. Performance Test Data by Means of Indirect Tensile Cracking Test for All Evaluated Mixtures.

4.1.2 Intermediate and Advanced Testing

Asphalt Pavement Analyzer Rut Test

Figure 10 shows the APA rut depth values at 64ºC and 8,000 loading cycles for the four asphalt mixtures as determined by the APA Rut test. Based on the data shown in Figure 10, Mixtures P1 and P2 exhibited similar rutting depths when compared to the control mixtures. This performance characteristic can be attributed to the plastomeric-modified binder which improved the stiffness property of the RPM asphalt mixtures. Meanwhile, the C1 mixture exhibited the highest susceptibility to rutting depth due to the use of unmodified virgin binder, while the C2 mixture fared better due to the use of SBS elastomeric modified binder, resulting in rutting resistance similar to P1 and P2 designs.

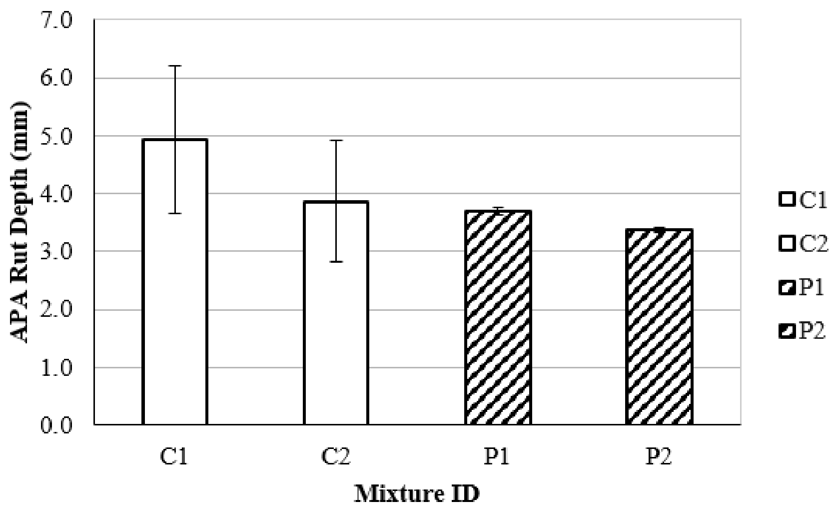


Figure 10. Performance Test Data by Means of Asphalt Pavement Analyzer Test for All Evaluated Mixtures.

Dynamic Modulus Test |E|*

The dynamic modulus test data simulate the temperature variation and applied traffic loading frequency occurring on interstate highways, primary and secondary roads, and intersections or areas with stop-and-go traffic. Based on the data presented in Figure 11, a difference between the E* for Mixtures C1 and C2 was observed, which could be attributed to the SBS elastomeric-modified binder. At higher frequencies and colder temperatures, Mixture C2 is slightly softer than Mixture C1. Mixture P1, which has the higher binder content (6.83% of total mix) that encompasses the 5% added plastics and virgin binder, is softer and has a higher recovery. Mixture P2 performs similarly to Mixture C1 at low temperatures and Mixture C2 at high temperatures.

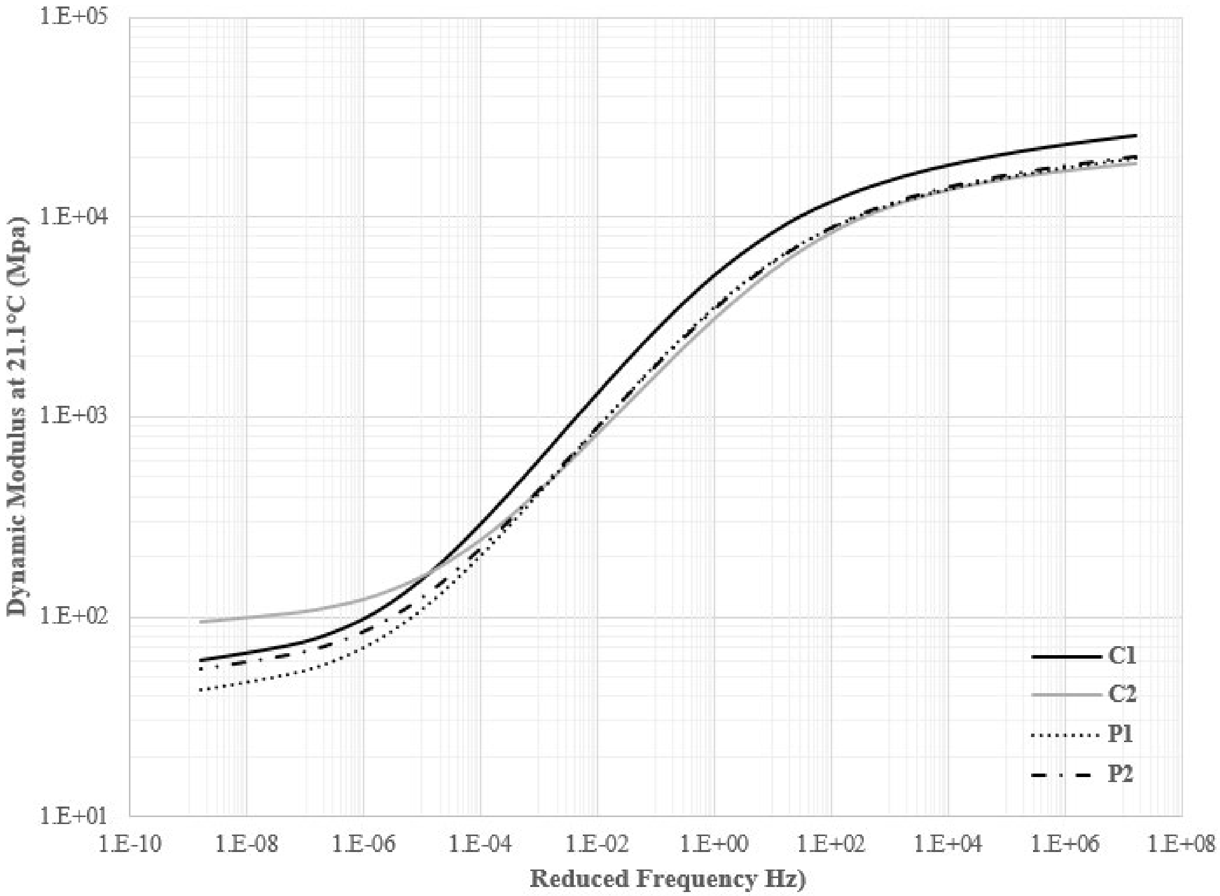


Figure 11. Performance Test Data for Dynamic Modulus for All Evaluated Mixtures.

The phase angle graph below (refer to Figure 12) was calculated from the dynamic modulus testing data using the time lag between stress-strain peaks and the reduced frequencies. The phase angle master curve shows the elastic versus the viscous performance of the asphalt mixtures in terms of temperature and frequency. Mixture C1 has the highest phase angle due to its 30% RAP content, while Mixture P1 has a similar performance to Mixture C1 as it includes 5% plastic as a replacement for part of the total binder weight, which increases its elasticity potential. The phase angle of Mixture C2 is lower than that of Mixture C1 due to the usage of SBS elastomeric-modified binder. Since a lower phase angle peak indicates a more elastic asphalt mixture, Mixture C2 is the most elastic asphalt mixture and is therefore better able to recover to its original configuration once an applied load is removed. Following Mixture C2 in elasticity is Mixture P2, while Mixtures C1 and P1 have almost identical phase angle peaks and elasticity.

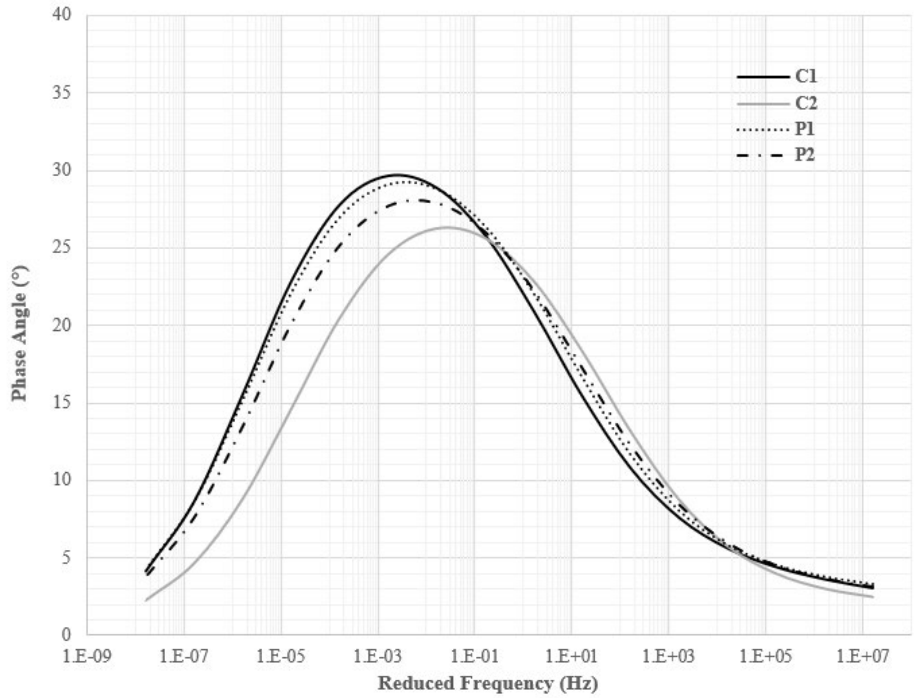
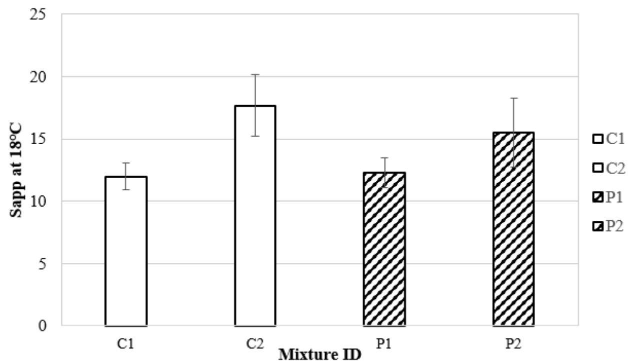
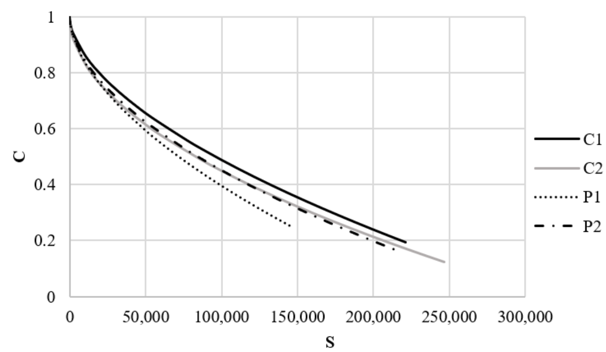


Figure 12. Performance Test Data for Phase Angle Master Curve for All Evaluated Mixtures.

Direct Tension Cyclic Fatigue Test

The results of the Direct Tension Cyclic Fatigue test are shown below in Figures 13 and 14. Figure 13 shows the S_{app}, or apparent damage capacity for each mixture. Figure 14 is the C vs. S curve (known as damage curve) for each mixture, where C is the pseudo- stiffness and S is the damage parameter at each loading cycle. The C vs. S curve shows that as stiffness decreases, damage increases for each of the asphalt mixtures until failure. It is more desirable to have a longer and flatter curve as this indicates that a mixture experiences damage gradually and takes longer to fail. Mixture P1 was the mixture that failed first while other asphalt mixtures follow a similar trajectory. Mixture C2 was the mixture which failed last, likely because of the SBS-modified polymer binder. A higher S_{app} value for an asphalt mixture correlates with better fatigue resistance. Figure 13 shows that Mixture C2 had the highest S_{app} due to the SBS-modified polymer binder. Meanwhile, Mixture C1 had the lowest S_{app} because it contains 15% additional RAP than the other mixtures, as RAP includes aged materials that are expected to have lower fatigue resistance when compared to virgin materials. Mixtures P1 and P2 have different S_{app} because of the different types and percentages of plastic additives used. While more plastic means a higher stiffness for Mixture P1, the plastic was not able to recover once damage was applied in the same way that the SBS-modified polymer binder in Mixture C2 could. This is why Mixture P1 had a low S_{app} value when compared to the S_{app} values of Mixtures P2 and C2.





Direct Tension Cyclic Fatigue Test: S_{app}.

Direct Tension Cyclic Fatigue Test: C vs. S Curve.

Stress Sweep Rutting Test

The results of the SSR test in terms of RSI are shown in Figure 15. A mixture with a lower RSI will have more rutting resistance than a mixture with a higher RSI. Looking at the two control mixtures, Mixture C2 had a lower RSI than Mixture C1 as a result of the SBS-modified polymer and is therefore less susceptible to rutting. Mixtures C1 and P2 have nearly identical RSI values, which means they have similar resistance to rutting. Between the two plastic mixtures, Mixture P1 had the lower RSI because it contains a higher percentage of plastic. More plastic leads to a stiffer asphalt mixture and higher resistance to rutting.

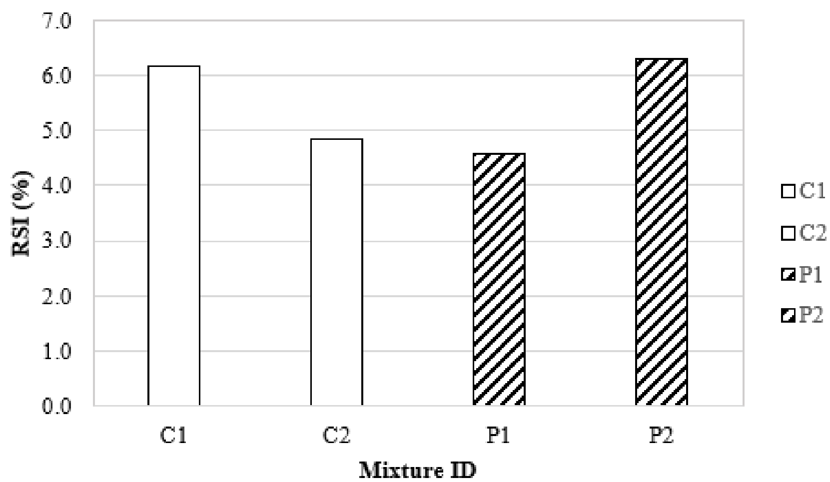


Figure 15. Performance Test Data by Means of Stress Sweep Rutting Test for All Evaluated Mixtures.

4.1.3 Summary of Experimental Results

Figure 16 presents a summary of the experimental results described in sections *4.1.1* and *4.1.2*, ranking the performances of the four tested asphalt mixtures from worst to best for each test. The mixtures that performed the best are at the top of each column while those that performed the worst are at the bottom. It was found that Mixture P1, which has a higher amount of plastic, performed better in tests that were focused on durability (Cantabro Mass Loss), cracking resistance (IDT-CT), and one of the rutting tests (SSR) due to its high stiffness. Mixtures P2 and C2 performed the best in tests that measured damage recovery (Direct Tension Cyclic Fatigue) and viscoelastic properties (|E*|) due to their mixtures being less stiff and, in the case of Mixture C2, incorporating an SBS-modified binder. For almost all the experimental tests except for IDT-CT, Mixture C1 performed poorly when compared to the other mixtures.

Worst to Best	Cantabro Mass Loss	IDT-CT	Asphalt Pavement Analyzer	Dynamic Modulus |E*|	Direct Tension Cyclic Fatigue	Stress Sweep Rutting
	P1	P1	P2	C2	C2	P1
	C2	C1	P1	P2	P2	C2
	C1, P2	C2	C2	P1	P1	C1
		P2	C1	C1	C1	P2

Figure 16. Summary of Asphalt Pavement Test Results, Mixture Performances Ranked.

4.1.4 FlexPAVE Mechanistic Software Simulation Results

The FlexPAVE analysis generated graphs showing the percent damage (for total, top, and bottom layers) versus time and rutting depth for each layer in the pavement section over time. As stated previously and for the purposes of this study, only the rutting depth in the top layer and percent damage from the top were considered for all cross sections other than Exp2-Section. This framing was used to focus the comparative analysis on the part of each roadway where RPM asphalt would be used. In contrast, Exp2-Section, where bottom-up and top-down cracking were both considered. Examples of the Percent Damage from Top versus Time and the Top Layer Rutting versus Time curve are shown in Figures 17 and 18.

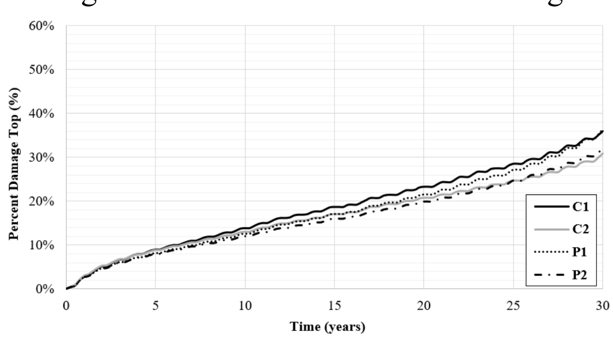


Figure 17. Percent Damage Curve for D-Section.

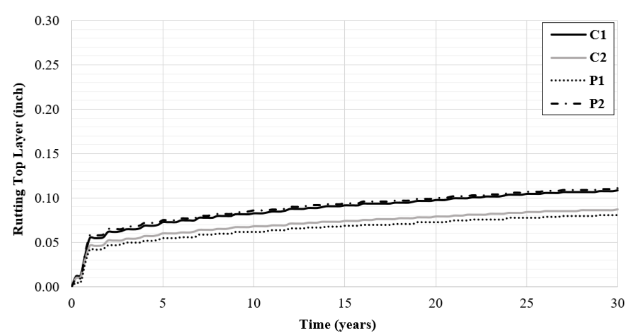


Figure 18. Rutting Curve for D-Section.

The lifespans of the four mixtures for each of the five pavement sections were determined from curves similar to Figure 17 and 18. Results are summarized in Table 5. Exp1-section showed the most cracking, earliest for each asphalt mixture, which resulted in a more significant percent damage of the asphalt surface layer by the end of each maintenance interval. This also correlates with a greater difference in the time taken for each surface mixture to reach the specified percent damage. Exp2-section follows a similar trend to Exp1-section. This is a result of the experimental sections consisting of a thicker layer of surface mix followed by a layer of crushed aggregate base with no additional intermediate or base asphalt layers. The E-section showed the next highest damage because of its high traffic levels and speeds, but there was less of a difference in the time taken for the mixtures to reach the specified cracking. The Low Volume-section showed the next greatest difference in asphalt mixture lifespan, and the D-section showed the least difference in asphalt mixture lifespan. In every pavement section, Mixture C1 performed the worst and Mixture P2 performed the best in terms of lifespan. Mixture P1 performed better than Mixture C2 in every pavement section except for in the experimental sections.

Table 5. Lifespans of Asphalt Mixtures C1, C2, P1, and P2 Based on Different Pavement Sections

D-Section			**Exp1-Section**		
Mix ID	**Damage (%)**	**Time (year)**	**Mix ID**	**Damage (%)**	**Time (year)**
C1	13.86	10.000	C1	21.37	10.000
C2	13.86	10.875	C2	21.37	13.745
P1	13.86	11.390	P1	21.37	12.708
P2	13.86	12.000	P2	21.37	15.740
E-Section			**Exp2-Section**		
Mix ID	**Damage (%)**	**Time (year)**	**Mix ID**	**Damage (%)**	**Time (year)**
C1	15.16	8.539	C1	23.02	10.000
C2	15.16	10.000	C2	23.02	13.750
P1	15.16	10.408	P1	23.02	13.397
P2	15.16	11.344	P2	23.02	16.450
Low Volume-Section					
Mix ID	**Damage (%)**	**Time (year)**			
C1	13.65	10.000			
C2	13.65	11.638			
P1	13.65	12.608			
P2	13.65	14.925			

4.2 Sustainability Comparison via Life Cycle Assessment (LCA)

Figures 19-23 summarize life cycle GWP impact estimates by asphalt mixture (C1, C2, P1, P2) for the various evaluated roadway cross-sections.. Within each figure, GWP impacts are broken out by stage [A1, A3, A5, B, C] to see how different processes contribute to the overall impacts. In each figure, Mixture C1 is used as the baseline comparator for Mixture P1 and Mixture C2 is used as the baseline comparator for Mixture P2 for all the pavement structures.

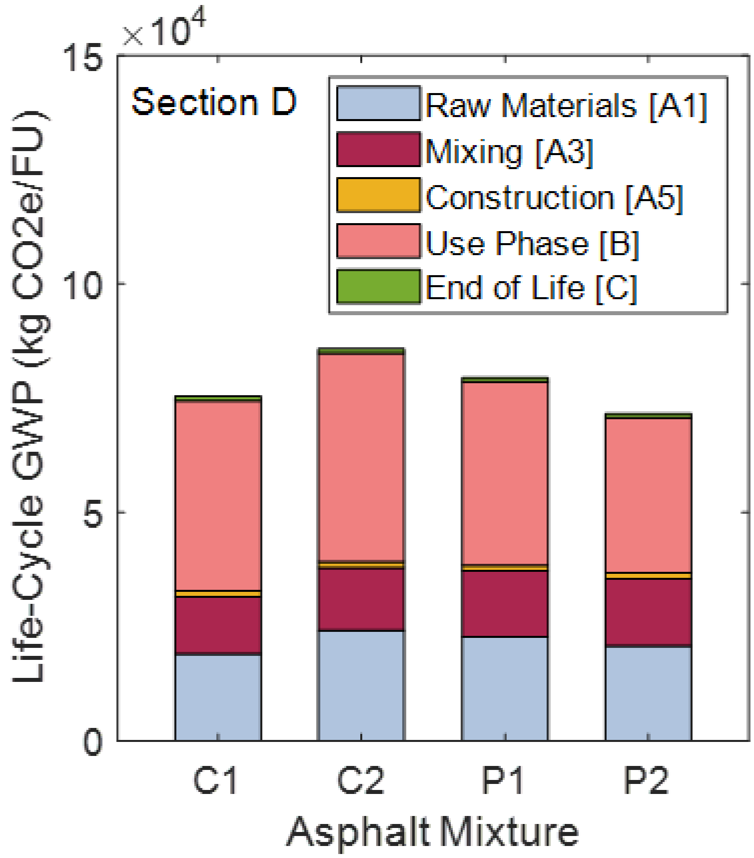


Figure 19. LCA GWP Impacts per Phase for D-Section. Note that GWP magnitudes are graphed x10^4, unlike all other figures, in which GWP is graphed to x10^5.

Figure 19 summarizes LCA results for the roadway D-section with surface layer depth of 1.5 inches. This cross section is typically used in secondary roads with 3-10 MESALs and a design speed limit of 45 mph. From the figure, Mixture C1 exhibits lower raw material supply (RMS) [A1] impacts due to its relatively higher RAP content compared to the other mixtures. The substitution of binder with plastic would result in slightly higher RMS [A1] impacts. However, the use and maintenance phase for Mixture C1 offsets the initial GWP reduction gained in RMS phase [A1]. Mixture C2 exhibits higher RMS [A1] impacts due to the high GWP impact of the implemented SBS-modified binder compared to the virgin binder and its supplanting PET (plastic #1) that were used in Mixture P2.

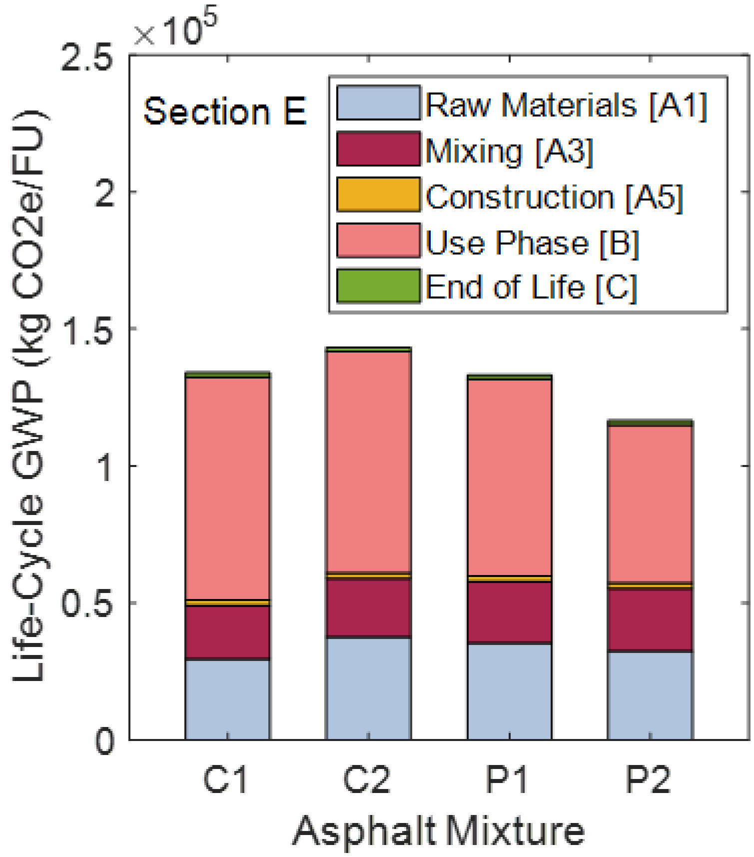


Figure 20. LCA GWP Impacts per Phase for E-Section.

Figure 20 summarizes the LCA results for the roadway E-section with a surface layer depth of 2 inches. This cross section is typically used in interstate or highways with 30 MESALs and a design speed limit of 65 mph. From the figure, the RMS [A1] impacts for Mixture C1 are relatively lower than Mixture P1. This difference can be attributed to the addition of plastics in the RMS phase [A1] but the initial increase in GWP impacts was offset by the corresponding decrease in impacts during the use phase [B]. Mixture P2 has lower GWP impacts in the use phase [B] compared to Mixture C2 which can be attributed to the supplanting of binder material with performance modifying PET (plastic #1).

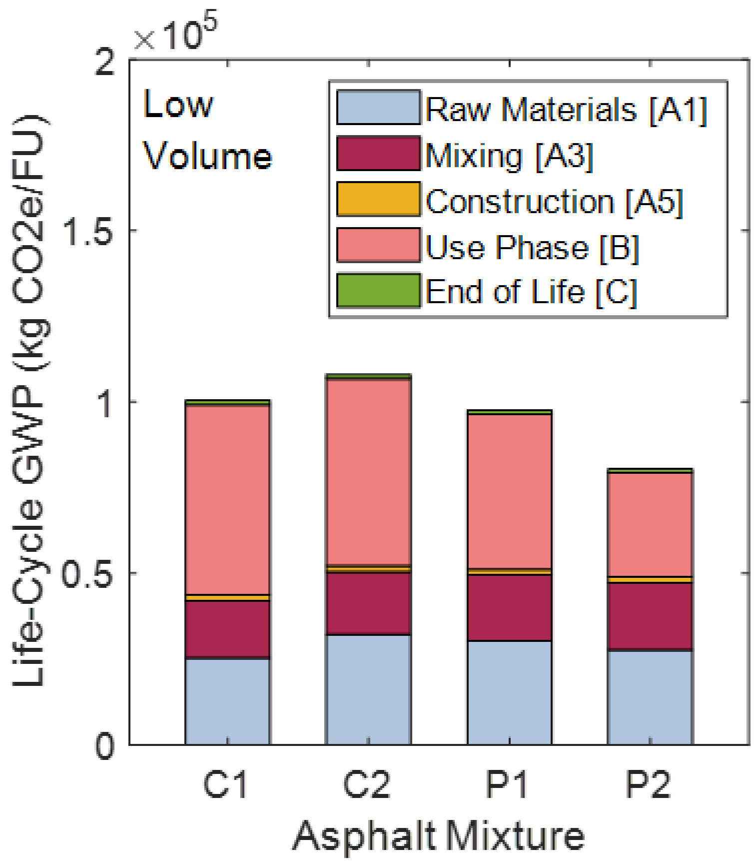


Figure 21. LCA GWP Impacts per Phase for Low Volume-Section.

Figure 21 depicts the LCA GWP impact results for the Low Volume-Section with a surface layer depth of 2 inches. This cross section is implemented in typically low traffic conditions of 3 MESALs, and a design speed of 35 mph. The figure shows a stark difference in GWP impacts for use phase [B] between Mixtures C2 and P2 and relatively lower GWP impacts in the RMS [A1] phase exhibited by Mixture P2. Mixture P1 shows relatively larger GWP in RMS [A1] phase compared to Mixture C1, but this is offset by the reduction in GWP impact in use phase [B].

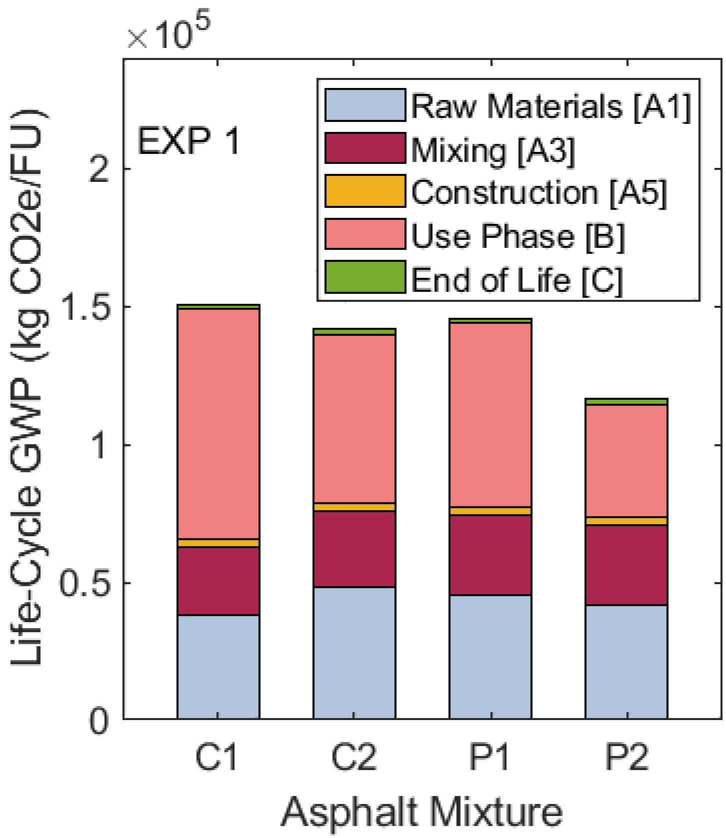


Figure 22. LCA GWP Impacts per Phase for Exp1-Section.

Exp1-Section was designed with a surface layer of 3 inches and the capacity to handle 10 MESALs and a design speed of 45 mph. Figure 22 exhibits low GWP impact of Mixture P2 during the use phase [B] compared to Mixture C2 while showing relatively low GWP impact in the RMS [A1] phase. However, Mixture C1 shows the lowest GWP impact in the RMS phase [A1] compared to the rest of the mixtures but this advantage is offset by the amplified GWP impact during use phase [B].

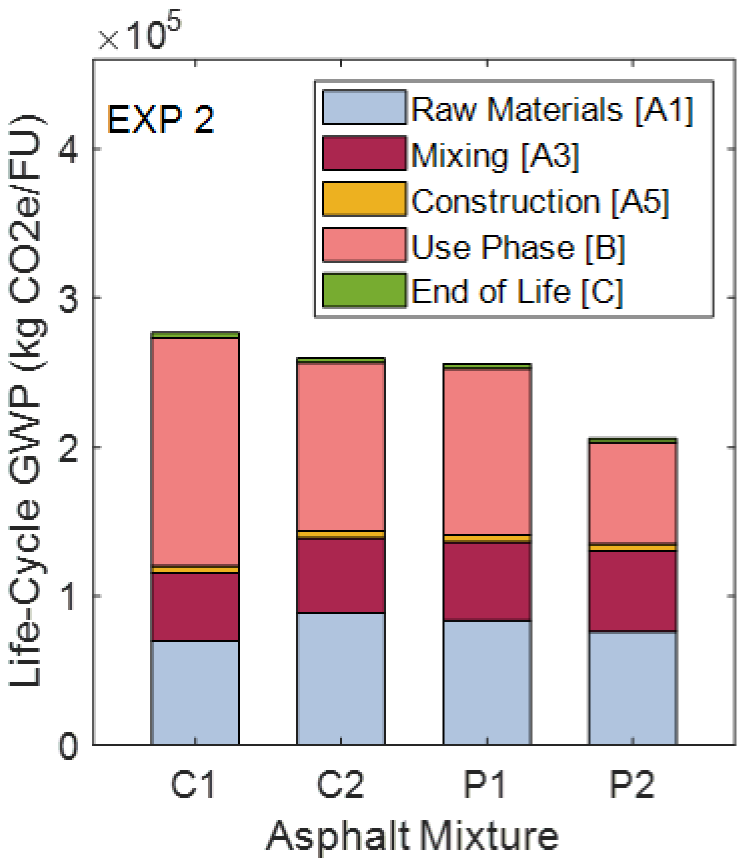


Figure 23. LCA GWP impacts per Phase for Exp2-Section.

Exp2-Section was designed with a surface layer of 5.5 inches without any intermediate and base layers beneath it. The cross section has the capacity to handle 10 MESALs at a speed of 45 mph. Figure 23 displays significantly lower GWP impacts during the use phase when paved with Mixture P2 as compared to Mixture C2. However, in the RMS [A1] phase Mixture C1 has a lower GWP than Mixture P1 which is again attributable to its 30% RAP content and absence of plastic substitution, albeit this benefit is negated by the higher GWP impact in the use phase [B].

4.3 Life Cycle GWP Impact as a Function of Lifespan Extension

The Life Cycle GWP impact figures above show how impactful the extension in asphalt mixture lifespan can be in reducing overall cradle-to-grave emissions, particularly in the use and maintenance phase. Figure 24 below shows the change in LCA GWP in kg CO_2eq./FU versus the asphalt mixture lifespan extension, both taken relative to their comparator per roadway cross section. The roadway cross sections of each data point is not specified in the graph as this figure is intended to show how an increase in asphalt mixture lifespan will positively impact the life cycle GWP of asphalt roadways if the extension is significant. Mixture P2, which has the longest extension in lifespan relative to the comparator for the Exp2-Section, maintains a life cycle GWP benefit with as little as a 1.3-year lifespan extension for the E-section. Mixture P1 has similarly beneficial results with life cycle GWP reduction, including only one instance of a life cycle GWP increase in the D-section.

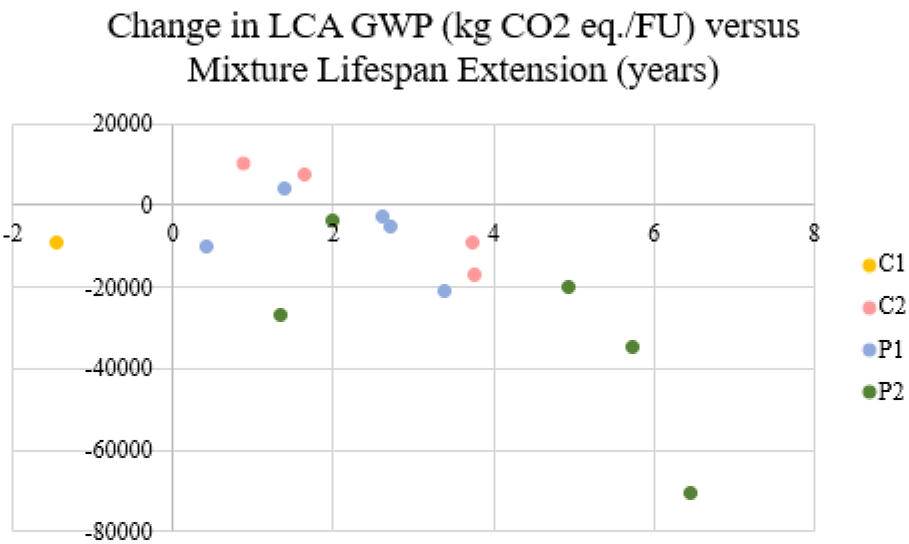


Figure 24. Change in LCA GWP versus Asphalt Surface Mixture Lifespan Extension.

5. CONCLUSIONS & FUTURE WORK

The use of plastic has increased exponentially over the past decades, resulting in vast amounts of plastic waste being sent to landfills or mismanaged in the environment. In order to address the plastic waste crisis and promote more sustainable construction materials, there is a potential solution to incorporate recycled plastic waste into asphalt pavement. Studies have shown that RPM asphalt pavement outperforms conventional asphalt mixtures in terms of taking longer to reach similar levels of surface damage. Additionally, while RPM asphalt mixtures have a higher initial life cycle GWP in the raw material supply phase, the increase in GWP is offset during the use and maintenance phase if the lifespan extension for RPM asphalt is significant relative to its comparator. However, the full life cycle GWP benefits of utilizing RPM asphalt opposed to conventional asphalt pavement can only be achieved if the entirety of the lifespan extension is used. This would require VDOT to reconsider their pavement rehabilitation schedule to address road conditions on a case-by-case basis instead of setting a fixed schedule of 8-12 years irrespective of pavement conditions. Regardless of if VDOT utilized the full lifespan extension for RPM asphalt, there are other potential benefits to using recycled plastic as an additive in asphalt pavement. The results of this study indicated that even when the use of RPM asphalt pavement resulted in a higher cradle-to-grave LCA GWP, it is not such an appreciable difference in GWP impact when considering that hundreds of pounds of plastic waste would find an end-of-life use in asphalt pavement. However, future work on RPM pavement characteristics needs to address challenges related to the slow release and loading of microplastics into the environment via stormwater runoff, the potential impact of plastics on asphalt recyclability once it reaches the end of its service life, and how RPM asphalt pavement roughness and surface texture may affect the vehicle fuel consumption.

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