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RECYCLED PLASTICS IN ASPHALT *PART A:* State of the Knowledge

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NATIONAL ASPHALT PAVEMENT ASSOCIATION

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RECYCLED PLASTICS IN ASPHALT *PART A:*
State of the Knowledge

1 INTRODUCTION

Over the past 50 years, the asphalt industry has used recycled waste products with varying levels of success. In fact, asphalt is one of, if not the, most recycled material in the United States with over 89 million tons of asphalt mixtures recycled back into new asphalt mixtures in 2019 (Williams et al., 2019). In addition to using reclaimed asphalt pavement (RAP), asphalt mixtures can also contain recycled tire rubber, steel slag, recycled asphalt shingles, recycled glass, and more.

Recycling is a concept most people across the United States support. They see it as a practice that can not only prevent the extraction and processing of non-renewable resources, but also potentially reduce the costs of manufacturing new products by utilizing new raw materials from a waste stream. Nonetheless, the conversation needs to shift from recycling in general to responsible recycling.

Recycling for the sake of recycling is not enough anymore – and this could not be truer when we consider infrastructure. Sustainability is a critical concept that has garnered much attention, but additional research efforts are needed to understand the true environmental impacts of recycling through life-cycle assessment. As the asphalt industry advances and makes strides to become an even more sustainable industry, responsible recycling is key to a more sustainable future. Instead of just recycling to recycle, partnerships between agency and industry, when armed with scientifically based research, can determine if recycled materials could benefit our infrastructure network. If so, recycling new raw materials from a waste stream into asphalt pavement mixtures would be a responsible action.

It has long been said there are three "E's" one must consider: engineering, environment, and economics. Recycling to remove a material out of the landfill and use it effectively in an asphalt mixture, while potentially being good for the environment, could have economic and engineering repercussions that can only be determined through research, which requires two things that most people are short on: time and money. However, there is current policy which asks industry and infrastructure owners to consider more than just the recyclability of a material before it is used in infrastructure projects.

The current Federal Highway Administration (FHWA)'s policy on recycled materials states:

1. Recycling and reuse can offer engineering, economic and environment benefits.
2. Recycled materials should get first consideration in materials selection.
3. Determination of the use of recycled materials should include an initial review of engineering and environmental sustainability.
4. An assessment of economic benefits should follow in the selection process.
5. Restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications. (FHWA, 2015).

This policy provides additional context as to what it takes to recycle responsibly. It takes research, collaboration, and time. When recycling is done responsibly, it is encouraged and even applauded. The process cannot be rushed. Data, time, and analysis are needed to vet technical merit.

1.1 The Beginning of the Plastic Crisis

In 2017, China passed the National Sword policy. This policy signaled a priority shift in the country, raising the level of interest in both environmental protection and human health. When the policy was enacted, China closed its borders to the import of waste plastics from other countries effective January 2018. Until that time, China had been serving as the final resting place for approximately 45 percent of the world's plastic waste. Annually, it is estimated that approximately 106 million metric tons of plastic waste will need to find a new home or end use. As such, the public, legislators, environmentalists, scientists are concerned that a reduction in plastic usage will not happen and that realistically 111 million metric tons of plastic waste will be displaced by the policy (Brooks et al, 2018). Currently, it is estimated that only about 9% of the world's plastic is recycled annually, with over 80% ending up in landfills or in the natural environment. Between 4 and 12 million metric tons of plastic waste find their way into the oceans annually (Geyer et al., 2017 & Jambeck et al., 2015).

Current trends in the United States echo those of the world stage. According to the EPA, plastics accounted for 35.4 million tons of waste in the United States in 2017 compared to 31.4 million tons in 2010. These 35.4 million tons are equivalent to approximately 13.2 percent of the total waste generation in the United States, and only 8.4 percent (3 million tons) of the plastic waste was recycled. This left 5.6 million tons to undergo combustion and 26.8 million tons to be landfilled. Just over 19 percent of all landfilled waste is plastic.

1.2 Is Asphalt Part of the Solution?

The urge to recycle has increased significantly over the past decades. Cities and counties have responded by banning plastic straws, restaurants have replaced plastic utensils with compostable forks, and people are now looking to asphalt as a potential home. Concurrently, the Plastics Industry Association's New End Market Opportunities (NEMO) for Film working group published a Literature Review: Using Recycled Plastics for Compounding and Additives (PLASTICS, 2018), which identified the use of plastic film waste in asphalt as a new potential end market opportunity based on previous research.

The American Chemistry Council (ACC) also set three goals to help encourage the plastic recycling effort.

1. By 2040, 100% of plastics packaging is reused, recycled, or recovered.
2. By 2030, 100% of plastics packaging is recyclable or recoverable.

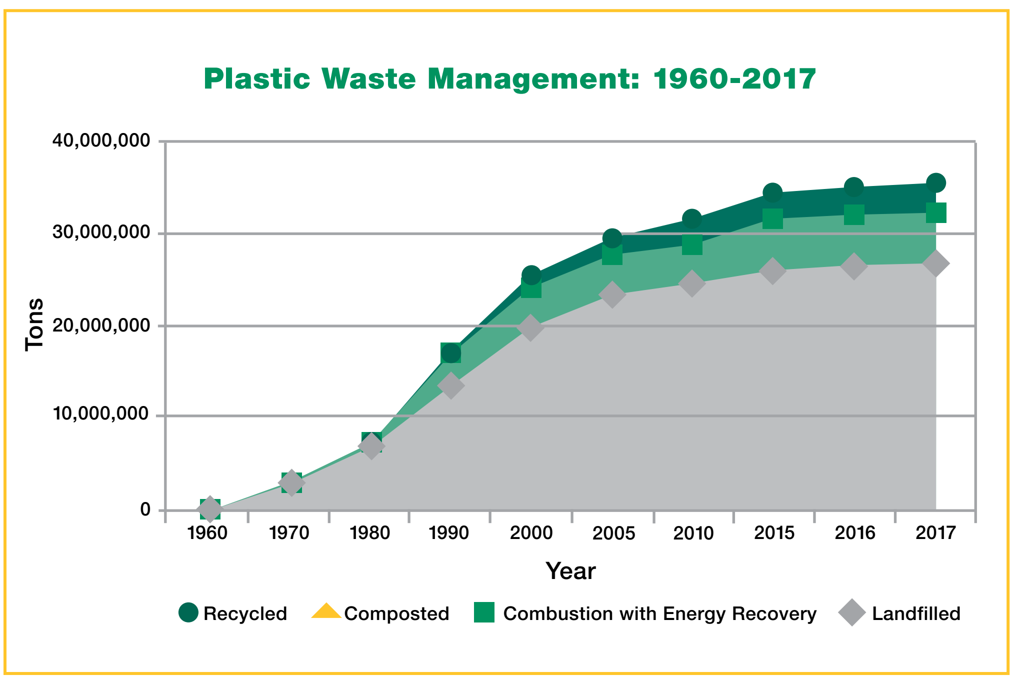


Figure 1-1. Plastic Waste Management: 1960-2017 (EPA, 2020)

3. By 2022, 100% of North American manufacturing sites operated by ACC's Plastics Division members will participate in Operation Clean Sweep-Blue to keep plastics out of waterways. (ACC, 2020).

As people asked for solutions to the visible plastic problem in landfills and the ocean, companies who had been developing recycled plastic materials for asphalt mixture and binder modification began marketing their products. Videos began going viral on social media, claiming plastic modified asphalt could significantly increase the life of asphalt compared to conventional mixtures. This solution would allow us to solve two of America's greatest issues: the plastic crisis and the aging infrastructure.

Before long, this message graduated from social media to more traditional print and electronic mediums. The September 13, 2018 issue of The Economist said, "Road makers turn to recycled plastic for tougher surfaces." The Washington Post asked and answered the following question: "Where does your recycled plastic go? Perhaps into future highways."

Then, on November 28, 2018, the topic took a legislative turn. At a hearing titled "Addressing America's Surface Transportation Infrastructure Needs," the Chairman of the Senate Committee on Environment and Public Works asked Robert Lanham, the then Vice President of the Associated General Contractors of America, about the use of recycled materials in roads, specifically discussing plastics, to build longer-lasting, more resilient infrastructure.

Other legislative efforts followed. When the Save our Seas 2.0 Act was introduced by the Senate, Section 305 directed the "Secretary of Transportation and EPA Administrator to enter in an arrangement with the National Academies of Sciences, Engineering, and Medicine to evaluate the feasibility and advisability of innovative uses of plastic waste in roadways, bridges and other infrastructure." House Resolution 288 of the 116th Congress also known as the Green Real Deal discussed "promoting the widespread use and deployment of next generation recycling and waste management technology, such as plastics-to-fuel initiatives, and transforming postconsumer recycled plastic into new materials such as asphalt."

While recent legislative efforts have been tailored back to support research and answer critical questions, early press and media made claims about the use of plastic modified asphalt without providing much data. People were asking, "Why are we not recycling?" instead of "Is it responsible to recycle?" The asphalt industry and state agencies have faced this type of dilemma before in their long history of using recycled materials, and there are important lessons that we can take moving forward.

1.3 Learning from the Past

Three materials really provide the most relevant cautionary tales (in some cases) and blueprints (in other cases) on how to successfully implement recycled materials into asphalt mixtures: recycled tire rubber (RTR), recycled asphalt shingles (RAS), and reclaimed asphalt pavement (RAP).

1.3.1 Recycled Tire Rubber

RTR, which is often used as smaller particles and referred to as ground tire rubber (GTR), is typically mixed with either asphalt binder or an asphalt mixture to improve the asphalt binder properties that will make it more resistant to rutting and/or cracking similar to polymers like styrene-butadiene-styrene (SBS). A product called asphalt rubber was really the first modern use of this recycled material in asphalt mixtures. It was introduced in the 1960s in Arizona as a field-blended product (McDonald 1975; McDonald 1978, Morris and McDonald 1976; Huffman 1980). In the late 1980s, other states began to look at the use of rubber-modified asphalts. Florida, for example, began a research program due to Senate Bill 1192 and showed that the rubber modification did improve the overall performance of the mix (Roberts et al 1989; Choubane et all 1999).

In 1991, Section 1038(d) of the Intermodal Surface Transportation Efficiency Act (ISTEA) federally mandated states to use a minimum amount of RTR each year beginning in 1994. While the mandate caused an increase in RTR usage, it also moved a material from the research phase to the implementation phase. In addition to the mandate coming ahead of the science, the industry was not able to properly use the material in the plant infrastructure of the time. Due to pushback, the mandate was removed in 1995 under section 205(b) of the National Highway System Designation Act. While RTR usage continued in some states, most discontinued RTR programs and did not reconsider again until 2008 when the price of polymers increased and states needed another option for asphalt modification. In 2019, a survey conducted of asphalt mixture producers only showed the use of RTR in 10 states (Williams et al., 2020).

1.3.2 Recycled Asphalt Shingles

RAS was first thought to be a potential replacement for asphalt binder in new asphalt mixtures in the early 1980s (Davis 2009). However, it was not until the cost of asphalt binder rose significantly in the mid-2000s when asphalt mixture producers and road owners really began to explore its use (See Figure 1.2). Between 2009 and 2012, the amount of RAS used in asphalt mixtures rose from 0.702 million to 1.863 million tons. In 2014, RAS usage hit an all-time high of 1.964 million tons, but then usage began to drop and in 2019 it was estimated that only 0.921 million tons of RAS was used in asphalt mixtures (Williams et al., 2019).

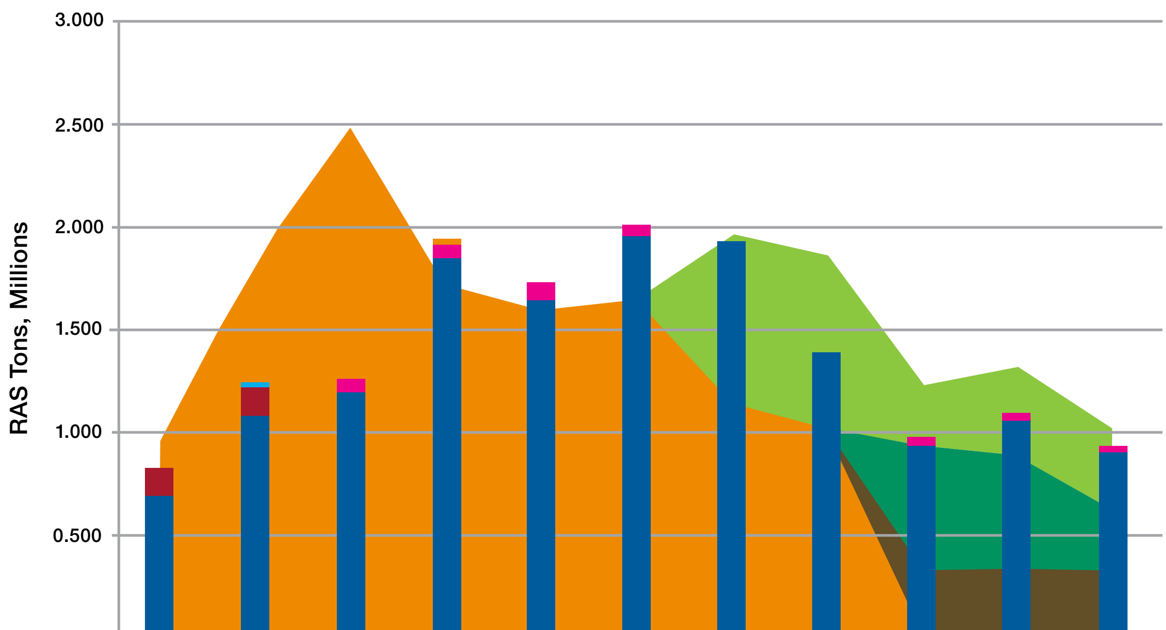
When RAS was introduced, states would commonly allow up to 5% RAS in new mixtures, with some states allowing as high as 7% or even 10%. For example, the Texas Department of Transportation (TxDOT) did a preliminary study which suggested RAS could be used in asphalt mixtures and would allow up to 5% in the surface mixtures and up to 10% in base mixtures, and developed an implementation plan (Texas Department of Transportation, 2020). In recent years, TxDOT has seen a decline in RAS use. RAS, when used properly, can perform well; however, there is a learning curve to using the product correctly. It is critical that contractors follow best practices and use the proper amounts for successful implementation.

Numerous studies and organizations have found that RAS can be used effectively, but these mixtures must be engineered to ensure that they will perform. This includes using well-characterized RAS and ensuring that the mixtures also contain enough virgin asphalt binder. Construction and production of these mixtures are also critical (Williams et al., 2019). As Figure 1.2 shows, the freefall on RAS usage has plateaued and seemed to stabilize over the past three years, but more confidence in the product will be needed if usage is expected to increase in the future.

1.3.3 Reclaimed Asphalt Pavement

RAP became a valuable material in the 1970s. The Arab oil embargo was driving up the price of crude oil, and the Federal Highway Administration (FHWA) responded by partially funding Demonstration Project 39 to use and document the use of RAP in pavements. Over the next 20 years, the National Cooperative Highway Research Program (NCHRP) and FHWA published guidelines and recommendations for the effective use of RAP in asphalt pavements (NCHRP, 1978; Epps et al., 1980; Sullivan, 1996; Kandhal and Mallick, 1997). Many states limited or even prohibited RAP usage early on because of early mixture failures. This is another example of how implementation should not precede science.

Further work continued to advance the use of RAP. NCHRP and state Departments of Transportation (DOTs) continued to fund research, which allowed the industry to understand how to use RAP effectively in mixtures in the late 1990s through the early 2010s (Soleymani et al., 2001; McDaniel and Anderson, 2001; Doyle et al. 2012), and years later, research was completed on how contractors and agencies could move to high RAP mixtures (West et al., 2013). Despite some countries in the world using high RAP mixtures effectively (West and Copeland, 2015), the average RAP content in the United States in 2019 was



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Processed Shingles Accepted	—	—	—	—	—	—	0.842	0.846	0.311	0.430	0.423
PCAS	—	—	—	—	—	—	—	—	0.591	0.534	0.277
MWAS	—	—	—	—	—	—	—	—	0.344	0.356	0.334
Unprocessed Shingles Accepted	0.957	1.851	2.500	1.724	1.599	1.664	1.129	1.027	—	—	—
Landfilled	—	0.007	0.000	—	—	—	—	0.005	—	—	—
Used in Other	0.123	0.125	—	0.012	0.005	0.006	—	—	—	—	—
Used in Cold Mix	—	—	—	—	—	—	—	—	—	—	—
Used in Aggregate	0.006	0.003	0.074	0.073	0.082	0.043	0.009	0.009	0.036	0.050	0.018
Used in HMA/WMA	0.702	1.100	1.192	1.863	1.647	1.964	1.931	1.390	0.944	1.053	0.921

Figure 1-2. Comparison of Tons of RAS Accepted and Tons of RAS Used or Landfilled (Million Tons), 2009-2019. Processed RAS Acceptance First Tracked in 2015. (Williams et al., 2020)

about 21% (Williams et al., 2020), which has steadily increased over the last decade as shown in Figure 1.3. While this is about a 5 percent increase from the 2009 value, additional research has recently been published that shows if/how contractors and agencies can use recycling agents to increase recycled material content without sacrificing pavement performance (National Academies of Sciences, Engineering, and Medicine, 2020; Hand and Epps-Martin, 2020).

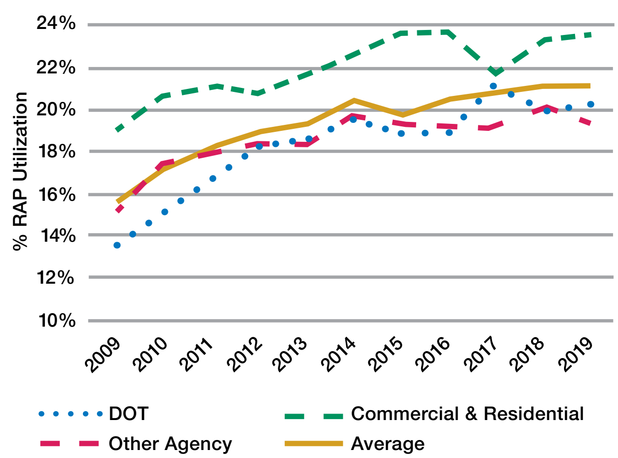


Figure 1-3. Average Percent RAP Used by Sector (Williams et al., 2020)

1.4 Summary

Right now, the asphalt pavement industry stands on the doorstep and is being invited to look at a new potential source of waste material for use in its product. The marketing says that it will be the next great thing and will increase the durability of our roadway networks. This document describes how asphalt paving technologists have been leaders in recycling for many years, summarizes several of the materials that have been recycled (or evaluated), and uses this history to provide some perspective on a topic of worldwide interest – recycling plastic. A prevailing theme is that logical decisions backed by engineering, science, technology and economics have led to successful outcomes, but that recycling for the sake of recycling may not be what is best for the longevity of our asphalt pavements or even be the most sustainable option. This report along with the accompanying synthesis document attempts to assess the current state of the knowledge regarding recycling plastics into new asphalt mixtures.

2 PLASTICS OVERVIEW

Before we can answer the question of recycling responsibly, we must understand the waste stream. This chapter characterizes the types and availability of plastics.

2.1 Types of Plastic

It is important to realize that recycling plastic is quite complicated. There are numerous types of plastic, and they have very different chemical compositions. This is just like there are numerous vehicles people can buy. Whether you buy a truck, minivan, or a motorcycle, each vehicle can get you where you want to go; however, what they do along the way will be completely different.

Currently, there are seven types of plastics, identified by resin identification codes (Table 2.1). These resins have different chemical and physical properties. For instance, one differences is melting point. All these polymers have many applications and many specific grades. This means the physical properties, including melting point, can vary depending on the exact composition. This variability adds uncertainty to the exact properties of any post-consumer resin (PCR) PCR stream. Packaging is often a multi-layer system that can contain different types of plastics. Food packaging contains sometimes seven or nine layers of bulk polyethylene. It can even contain polyamide, which has a higher melting point. This adds additional complexity to understanding the type of plastic being recycled.

Melting point is one characteristic important to use in asphalt because, if recycled plastics are supposed to modify asphalt binders, they will need to melt and become part of the binder. However, most asphalt mixtures are produced under 350°F (177°C). Some plastics may not even melt in a typical asphalt plant to blend with the binder or coat the aggregate.

Human health is another factor to consider when discussing running plastics through an asphalt plant. For example, when polyvinyl chlorine (PVC) is heated, it can generate polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) in the exhaust gasses. These dioxins can be harmful for human health and, thus, PVC use in asphalt mixtures should be avoided for health and safety reasons (Sun et al., 2003).

Table 2-1. Resin Identification Codes of Plastics (Standard; ACC 2020)

Number	Types of Plastics	Application/Uses	Melting Point (°C)	Melting Point (°F)
1	Polyethylene Terephalate (PET)	Bottles for water and soda; Food packaging; Food containers	>250	>482
2	High Density Polyethylene (HDPE)	Plastic mailing envelopes; Flexible pipes; Plastic chairs/stools; Toys and playground equipment; Plastic bags; Shampoo bottles	130 but can vary in grade	266 but can vary in grade
3	Polyvinyl Chloride (PVC)	Pipes; Electric cables; Construction material; Sign boards; Vinyl flooring	100-260	212-500
4	Low Density Polyethylene (LDPE)	Trays and containers; Plastic wraps; Plastic bags; Juice and milk containers	110-120	230-248
5	Polypropylene (PP)	Plastic hinges; Piping system; Plastic Chairs; Reusable plastic containers; Plastic moldings	160-165	320-330
6	Polystyrene (PS)	Food packaging; CD and DVD casing; Disposable utensils; License plate frames; Foam beverage cups	Glass Transition at 100	Glass Transition at 212
7	Other (Polycarbonate – PC; Polylactide – PLCA; Acrylonitrile Butadiene Styrene – ABS; Nylon; Fiberglass; Acrylic)	Baby bottles; Car parts; Water cooler bottles; Food containers	Based on grade and plastic type	

Figure 2.1 shows the breakdown by plastic type in municipal solid waste (MSW). The most common plastic found in MSW is polypropylene (PP) at 32.1 percent. Most research suggests PE is the primary plastic that could be incorporated into mixtures. Other plastics might melt, but could release toxic fumes or be incompatible. LDPE, Linear Low-density polyethylene (LLDPE) and HDPE only account for 29.2% of plastics in MSW (EPA, 2017).

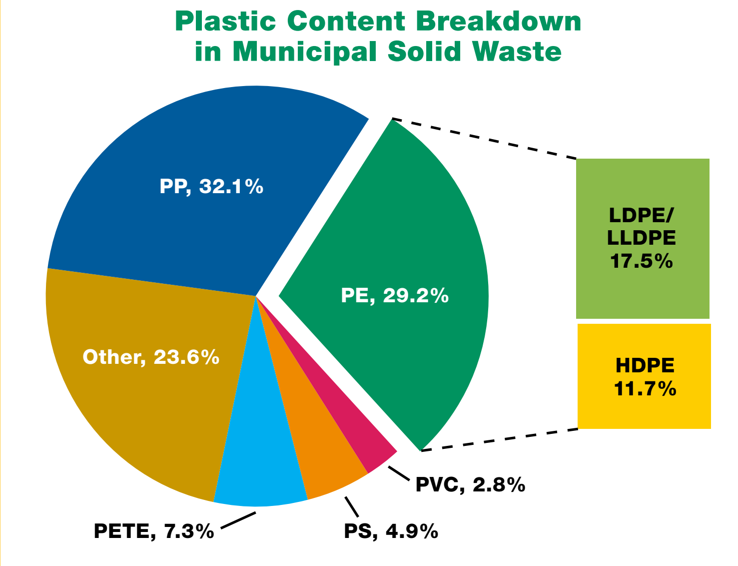


Figure 2-1. Plastic Content Breakdown in Municipal Solid Waste (DuBois, 2020; Based on EPA 2017)

2.2 Brief Overview of Recycling Plastics

Plastic recycling starts with the collection of post-consumer and manufacturer's waste plastic. Manufacturer's waste is typically recycled easier than post-consumer waste because it is cleaner and requires less sorting. When plastic is collected post-consumer, recycling companies typically obtain the plastic from municipal solid waste drop-off or pick-up locations (d'Ambrieres, 2019).

Once plastics are collected, they must be shredded, washed, and decontaminated. This process involves moving the plastic through a series of shredders to create plastic flakes. Different shredders can be used for different plastic types. When recycling plastics, plastic films tear and could carry other contaminants with them through the recycling process. They can also clog up shredders and damage the equipment.

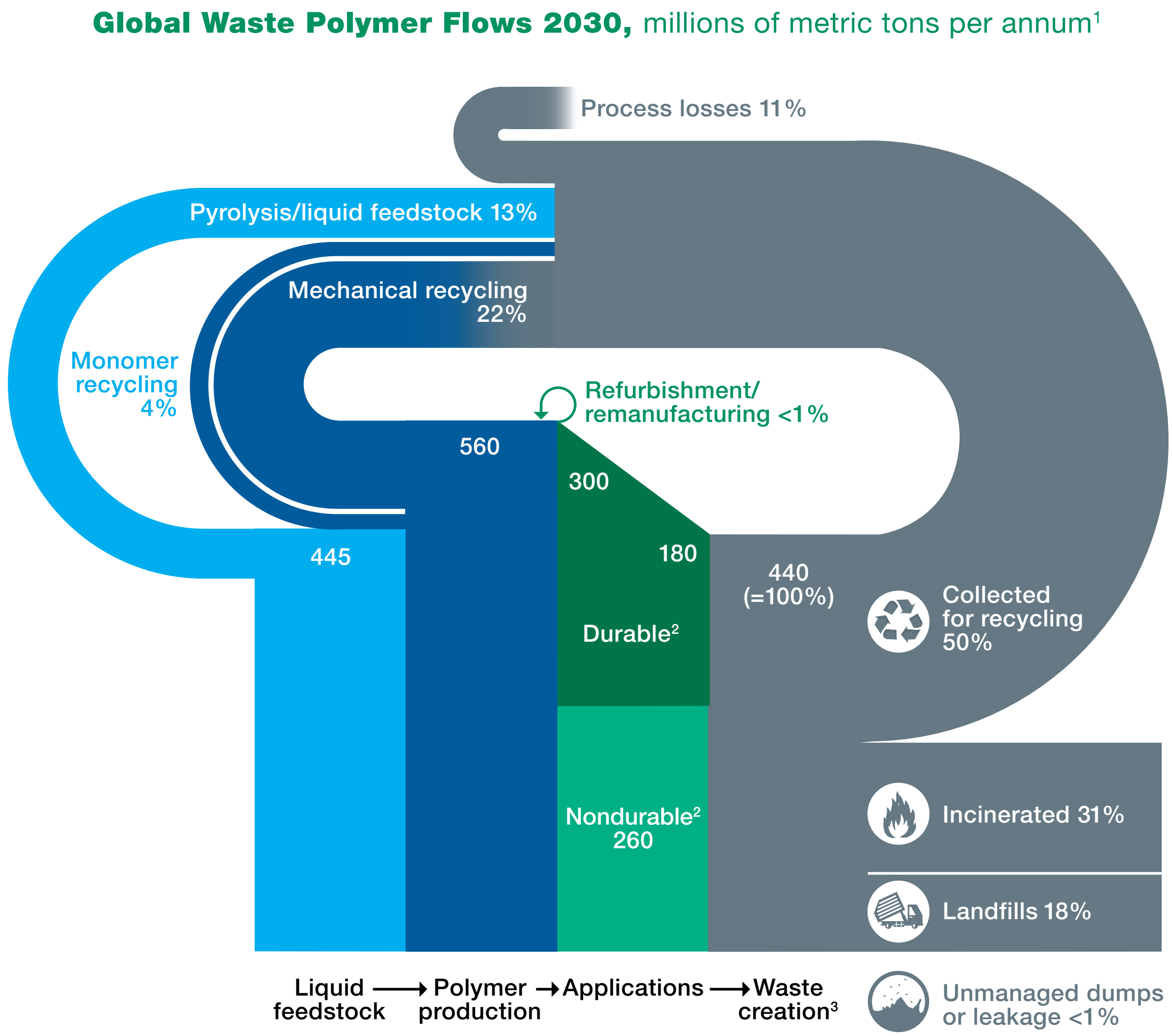
Since plastics can contain chemical or biological contaminants, standards are in place to regulate the reuse of plastics that could have been in contact with food. Many recycling companies add an additional step in the decontamination process after washing to ensure these standards are met (Kolek, 2001).

Once the plastic flakes have been resized and decontaminated, they are identified and separated based on the properties. Separation properties typically include density, air classification (how thick or thin the particle is), melting point, and color. In many cases the plastics are then compounded into a new form. This could be a pellet or another formation, but these products will then be used to produce new plastic products or potential modifiers for asphalt mixtures (Greentumble, 2018). The more processing that takes place, the greater the costs are going to be. Ultimately, in a low-bid environment, these costs must be recouped somewhere.

2.3 Ongoing Efforts for Recycling

Currently, the U.S. lacks the infrastructure needed to adequately recycle all the waste stream. In November 2019, House Resolution 5115 was introduced. The Realizing the Economic Opportunities and Values of Expanding Recycling (RECOVER) Act would allocate $500 million to matching federal grants cities, states, and tribes in an effort to advance the recycling infrastructure. Environmental Protection Agency funds would also be prohibited from being tied to plastic-derived fuels.

McKinsey & Company conducted an analysis in 2018 to estimate what it would take to achieve a 50 percent reuse and recycling rate by 2030. Using the assumptions shown in Figure 2.2, it was estimated that a $15-20 billion investment would be needed in the waste-recovery process per year. This estimate, which only accounts for plastic recycling, dwarfs the values proposed by the RECOVER Act. While this may seem insurmountable the same study indicates that globally, the petrochemical and plastics industry have been investing between $80 and $100 billion annually for the past decade (Hundertmark et al., 2018).



[1]Scenario based on a multi-stakeholder push to boost recycling, regulatory measures to encourage recycling, consistent progress on technologies, and $75-per-barrel oil price.

[2]Durable applications with an avarage lifetime > 1 year will end up as waste only in later years, while nondurable applications go straight to waste.

[3]260 million metric tons of mixed plastic waste from nondurable applications that end up as waste in same year plus 180 million metric tons of mixed plastic waste from production in previous years.

Figure 2-2. Global waste polymer flows for 2030 (Hundertmark et al., 2020)

2.4 Summary

When discussing recycling plastics in asphalt, one must understand the current dynamics of the plastic recycling landscape. The physical and chemical properties of some plastics may preclude their use in asphalt mixture due to either the negative reaction or lack thereof to the heat of asphalt plants. Additionally, significant investments into the plastic recycling infrastructure are needed to move the industry from its current recycling percentages to a 50 percent recycling or reuse rate. As research continues on the appropriate use of plastics in asphalt, a parallel effort would also be required to ensure that the infrastructure is in-place to economically recycle the 30% of the plastic waste stream that might be appropriate for use in asphalt mixtures. Additionally, if we assume that there are 38 million tons of LDPE or HDPE available per year, more than 10% of every asphalt mixture would need to be plastic to consume all the LDPE and HDPE in the U.S.

3 SUMMARY OF LITERATURE REVIEW FINDINGS

A comprehensive literature review was conducted on the use of recycled plastics in asphalt binders and mixtures. This review included over 110 research reports, journal articles, trade publications, newsletter and magazine articles, and personal email communications, all written in English. It should be noted that there is likely more literature available on this topic, but they are in languages other than English and thus were not included in this literature review.

Figure 3.1 through Figure 3.5 present the classification of literature documents based on year of publication, place of publication (i.e., country of the first author), type of recycled plastics, method of incorporating recycled plastics into asphalt, and scope of the study. Approximately 70 percent of the literature was published within the past 10 years (i.e., from 2011 to 2020). The five countries with the most literature documents are the United States, India, Malaysia, Canada, and China. Polyethylene (PE), including linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), and high-density polyethylene (HDPE), was the most studied type of recycled plastic for use in asphalt, followed by polyethylene terephthalate (PET) and polypropylene (PP), respectively. Over 60 percent of the literature added recycled plastics into the asphalt binder via the wet process (including Novophalt® and Polyphalt®), and approximately 30 percent used the dry process of adding recycled plastics into the mixture.

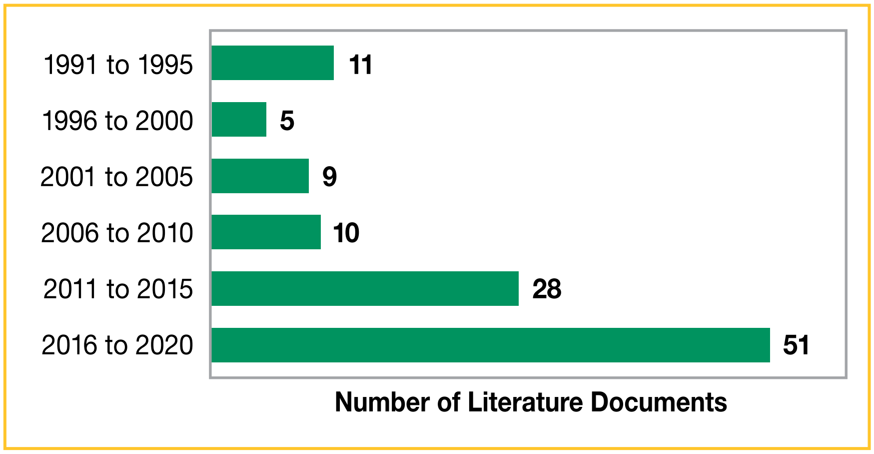


Figure 3-1. **Classification of Literature Documents based on Publication Year**

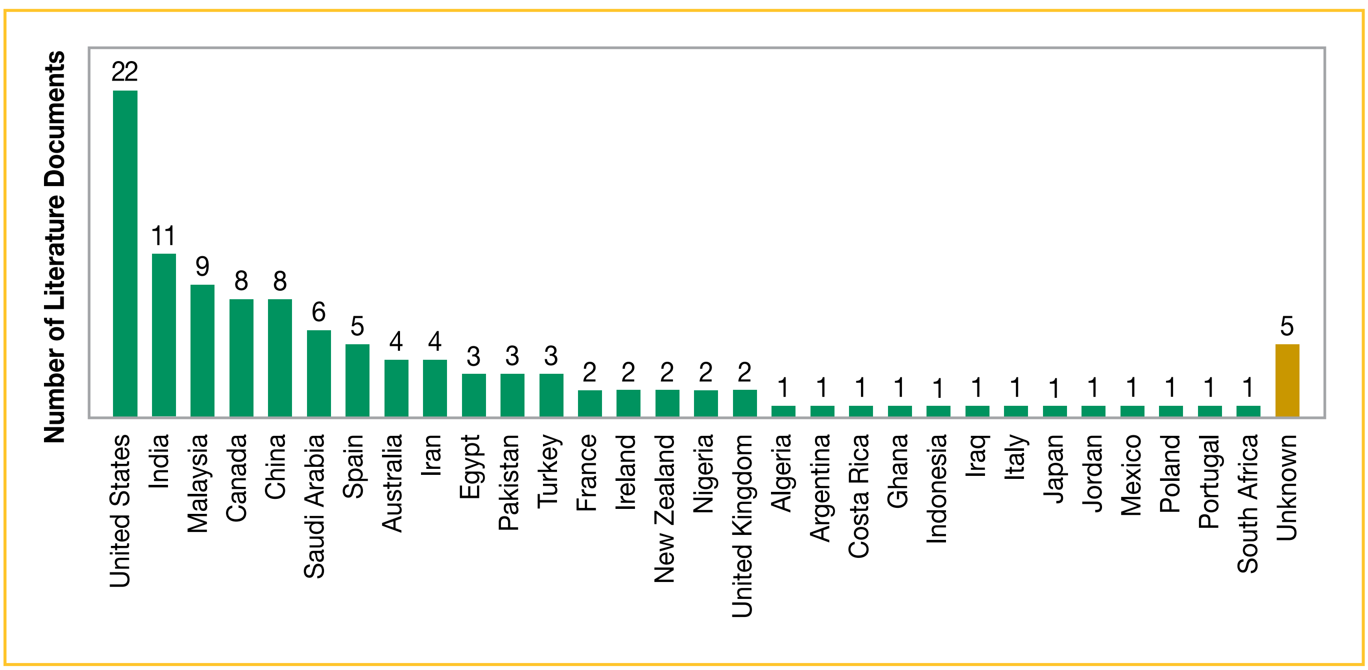


Figure 3-2. **Classification of Literature Documents based on Place of Publication**

Only a few studies reported the use of asphalt-plastic emulsion and plastic synthetic binder for adding recycled plastics. Finally, over 90 percent of the literature focused on laboratory testing and/or field project of recycled plastic modified (RPM) asphalt binders and mixtures, while the rest provided literature review, cost analysis, pavement design, production information, accelerated pavement testing, and agency specification.

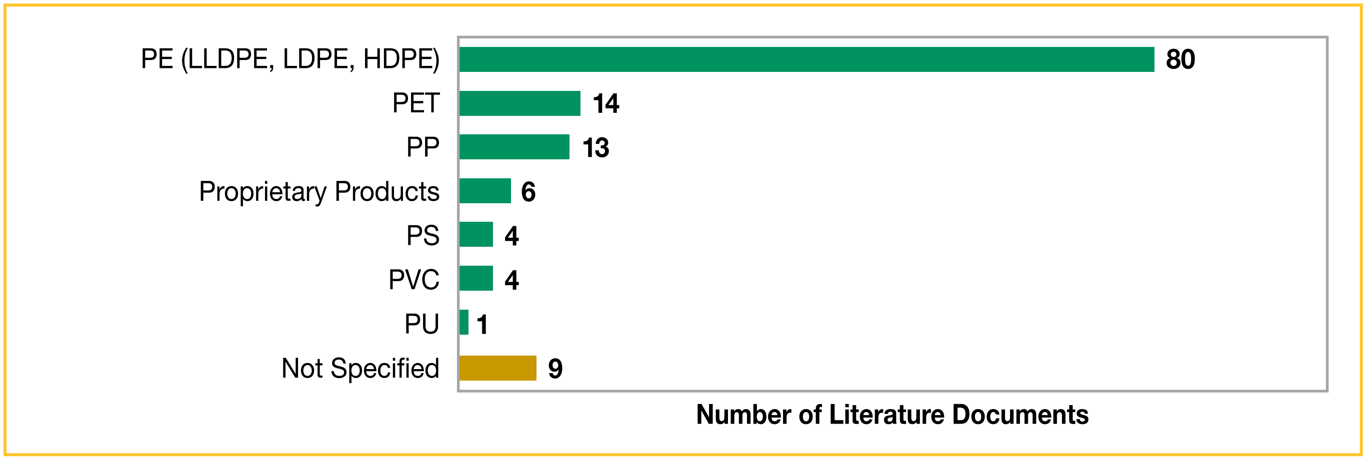


Figure 3-3. **Classification of Literature Documents based on Type of Recycled Plastics**

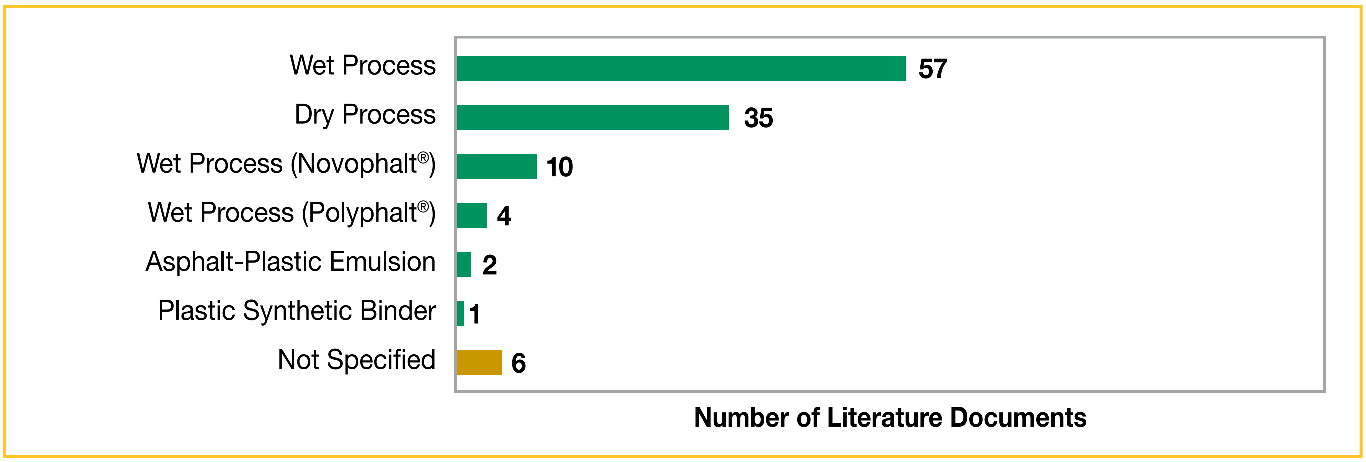


Figure 3-4. **Classification of Literature Documents based on Methods of Incorporating Recycled Plastics**

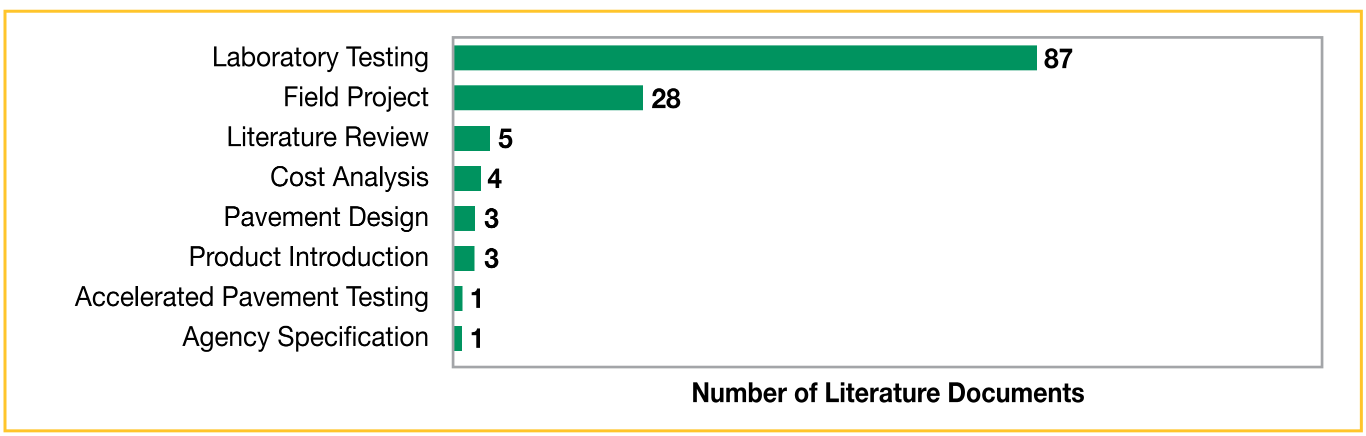


Figure 3-5. **Classification of Literature Documents based on Scope of the Study**

The following sections present a summary of literature review findings organized on a topical basis. These findings reflect the state-of-the-science from the literature, but do not necessarily represent the views of the authors, National Center for Asphalt Technology (NCAT), National Asphalt Pavement Association (NAPA), or Asphalt Institute (AI). For each individual document included in the literature review, a summary table and a synthesis are provided in an annex to this document.

3.1 Methods of Incorporating Recycled Plastics

In general, there are two methods of incorporating recycled plastics in asphalt: the wet process and the dry process. In the wet process, recycled plastics are added into the asphalt binder as polymer modifiers or asphalt replacement (in some cases, erroneously referred to as asphalt extenders), where mechanical mixing is required to achieve a homogeneous modified binder blend. Recycled plastics with a low melting point, such as LLDPE, LDPE, and HDPE, are typically suitable for this process. For the wet process, the dosage of recycled plastics commonly reported in literature varies from approximately 2 to 8 percent by weight of asphalt binder. This dosage corresponds to about 2 to 8 lbs. of recycled plastics in a ton of asphalt mixture.

In the dry process, recycled plastics are added directly into the mixture as either aggregate replacement, mixture modifiers, binder modifiers, or any combination thereof. The aggregate replacement approach is commonly used with recycled plastics with a high melting point (i.e., above the typical production temperature of asphalt mixtures), such as PP, PET, polystyrene (PS), and polycarbonate (PC), while the mixture modifier approach is applicable to virtually all types of recycled plastics (e.g., PE, PP, PET, PP, PS, and others) except for polyvinyl chloride (PVC) due to the concern of hazardous chloride emissions. When recycled plastics with a melting point below the mixture production temperature (e.g., LLDPE, LDPE, and HDPE) are used for mixture modification via the dry process, they will melt upon mixing with the hot aggregates and produce plastic-coated aggregates with potentially improved physical and surface characteristics. Previous experience of asphalt contractors in France indicated that when LDPE was added into the asphalt mixture via the dry process, part of the plastics coated the surface

of aggregate particles while the rest was dispersed in the asphalt mortar phase. For the dry process, the dosage of recycled plastics commonly reported in literature varies from approximately 0.2 to 1 percent by weight of aggregate, which corresponds to about 4 to 19 lbs. of recycled plastics in a ton of asphalt mixture.

3.2 Laboratory Binder Characterization

Every study that evaluated the impact of recycled plastics on asphalt binder performance expressed its findings in terms of penetration, softening point, viscosity, ductility, or performance grade. The overall consistent finding was that the use of recycled plastics for asphalt modification reduced the penetration and ductility and increased the softening point, viscosity, and high-temperature performance grade of asphalt binder. Therefore, asphalt binders modified with recycled plastics could potentially have better rutting resistance. However, other than reduced ductility, very few studies examined the effect of recycled plastics on asphalt binder properties related to fatigue or low-temperature cracking susceptibility.

The inherent incompatibility expressed in terms of phase separation between the recycled plastics and asphalt binder was another topic often evaluated in literature for the wet process. This incompatibility is mainly attributed to the difference in solubility parameter and thermodynamics between the two individual components. Phase separation refers to the tendency of polymers to separate from the asphalt binder under static heated storage conditions, which is an important attribute of polymer modified asphalt to maintain its integrity and homogeneity during storage, handling, and mixture production. The evaluation of phase separation typically required the storage stability testing (ASTM D7173) of plastic modified binders followed by softening point, viscosity, and rheological testing of the top-third versus bottom-third cigar-tube samples, sometimes in conjunction with fluorescence microscopy analysis. The literature consistently reported that producing a homogenous and storage-stable binder blend was difficult because the plastic modified binder was very susceptible to phase separation. To overcome this issue, several researchers incorporated a third component in the binder blends to act as a stabilizing agent or a compatibilizer. Potentially effective stabilizers and compatibilizers identified in the literature include ethylene-vinyl acetate (EVA), maleic anhydride (MA) grafted LLDPE, nanosilica, organic montmorillonite, polyphosphoric acid (PPA), reactive elastomeric terpolymer (RET), and styrene-butadiene-styrene (SBS). Low-level chlorination and maleation of PE were also found effective in improving its compatibility with asphalt binder. Among these potential stabilizers and compatibilizers, use of elastomeric polymers can enhance the performance grade and elasticity of RPM asphalt binders. Finally, one study reported that PE was insoluble in solvents commonly used in the chromatography and spectroscopy characterization techniques for polymers and asphalt binders, which further complicated the chemical characterization of asphalt binders containing recycled plastics and made solvent extraction and recovery infeasible.

3.3 Laboratory Mixture Characterization

Many of the existing studies evaluated the effect of recycled plastics on asphalt mixture behavior using the Marshall stability test. In most cases, the addition of recycled plastics increased the Marshall stability and the Marshall stability index (or quotient) of asphalt mixtures. Several researchers suggested that this indicated improved resistance to permanent deformation. Existing studies also demonstrated a positive impact of adding recycled plastics on the stiffness and rutting resistance of asphalt mixtures. The cause of this improvement, however, may differ depending upon how recycled plastics are added. In the wet process, recycled plastics provides a stiffening effect on the asphalt binder, which contributes to increased stiffness and rutting resistance of the resultant asphalt mixtures. In the dry process, the improvement in mixture rutting resistance has been mainly attributed to increased internal friction within the aggregate structure, enhanced aggregate quality due to the surface coating of aggregates with plastics, stiffening of asphalt binder due to plastics modification, or any combination of the above. Numerous studies suggested that plastic-coated aggregates had better toughness, abrasion resistance, bond strength, and reduced asphalt absorption, which yielded asphalt mixtures with better rutting resistance. Not many studies investigated the impact of recycled plastics on

the fatigue and cracking resistance of asphalt mixtures and they did not reach a consistent conclusion. Finally, only a few studies evaluated moisture damage resistance, with most of them concluding that recycled plastics had either a positive or no noticeable impact on the moisture resistance of asphalt mixtures.

3.4 Plant Operations

Existing studies that documented asphalt plant operations were mostly related to the production of Novophalt®, which is the trademark of a proprietary product marketed as an asphalt mixture modified with virgin or recycled PE. To overcome the phase separation of Novophalt® binder during storage, a mobile high-shear blending unit was developed to accommodate the on-site formulation of PE modified binders at asphalt plants during production. The Novophalt® blending unit was equipped with agitation and mixing tanks to ensure the homogeneity of asphalt binder until it was mixed with aggregates. Field experience indicated that the Novophalt® blending unit was not difficult to set up and could be completed within hours. During production, the blending unit was typically attached to the asphalt plant with one hose connected to the asphalt intake line and the other connected to a return line. Besides the blending unit, no additional plant modifications were required to produce Novophalt® mixtures.

3.5 Construction

Only one study in literature discussed the construction of asphalt mixtures modified with recycled plastics. The study claimed that high-modulus asphalt mixes produced with PE modification were difficult to compact due to increased binder viscosity and mixture stiffness, and thus, heavy rollers were required for construction in order to achieve adequate in-place density. Previous experience of asphalt contractors in France indicated that the compaction of PE modified asphalt mixtures was temperature sensitive; in general, field compaction was not an issue if it could be completed before the asphalt mat temperature dropped below the crystallization temperature of PE.

3.6 Health and Safety

The literature review identified two potential health and safety concerns regarding the use of recycled plastics in asphalt: leaching of toxic components during processing of recycled plastics, and the generation of chlorine-based gases from PVC during mixture production and construction. One laboratory study evaluated the leachability of hazard chemicals and toxic fumes (e.g., toluene, benzene, as well as aliphatic, cyclic, and aromatic hydrocarbons) generated by asphalt binders modified with three proprietary plastic products but found no detectible adverse effects from the recycled plastics.

3.7 Environmental Impact

The literature review suggested that recycling of waste plastics provides significant environmental benefits, such as preservation of limited natural resources, reduction of energy consumption, reduction of disposed and discarded solid waste, and reduction of carbon dioxide (CO2), sulphur dioxide (SO2), and nitrogen oxide (NO) emissions. However, these claims were not quantified. Also, the use of recycled plastics in asphalt has raised several environmental concerns, including the release of microplastics, jeopardizing the future recyclability of asphalt mixtures containing recycled plastics, compatibility and storage stability of RPM asphalt binders, and the material's life cycle sustainability. No study has yet investigated these perspectives.

3.8 Field Projects

Approximately 200 field projects using recycled plastics in asphalt pavements were identified in literature. There were reportedly more projects constructed in France between the mid-1980s and mid-1900s, but they were not identified due to lack of published records in English. Most of the field projects identified in this literature review were constructed using Novophalt® in more than a dozen countries between the late 1980s and the early 2000s. The Novophalt® projects included city streets, county roads, minor and principal arterials, interstates, and airports. Limited field performance data suggested that Novophalt® pavement sections performed well, especially in terms of rutting performance, although one study reported more cracking compared to pavement sections using unmodified and SBS modified binders. In 1993, a Novophalt® test section constructed on the FHWA's accelerated loading facility had the best rutting performance among all test sections included in the study.

India has reportedly over 15 years of experience recycling waste plastics in asphalt pavements, with more than 2,500 km of roads using asphalt mixtures containing plastic-coated aggregates. Although several studies reported a successful outcome of using plastic modified mixtures, field performance data for these pavement sections was not documented. More recently, numerous demonstration projects using proprietary products made of recycled plastics were constructed in Australia, Canada, Indonesia, the Netherlands, New Zealand, South Africa, the United Kingdom, and the United States. Many of these projects are only a few years old, and thus, the long-term durability of the pavements has yet to be determined.

4 KNOWLEDGE GAPS AND FUTURE RESEARCH

This chapter summarizes the knowledge gaps and recommendations for future research based on a critical review and analysis of literature on the use of recycled plastics in asphalt. The chapter starts with an executive summary of high-priority knowledge gaps and questions and then provides more detailed discussions on a broader range of future research needs on a topical basis. Information provided in this chapter is of importance to advance the development of science and knowledge as well as the implementation of using recycled plastics in asphalt.

4.1 Executive Summary of High-priority Knowledge Gaps and Questions

It is important to specify the source, recycling process, and properties of recycled plastics for use in asphalt binders and mixtures. At a minimum, acceptance limits should be established on the consistency, cleanliness, and particle size of recycled plastics. The physicochemical properties of recycled plastics that are important for asphalt applications include, but are not limited to, flow properties such as its melt flow index (MFI), melting temperature, percent crystallinity, specific gravity, ash content, and particle size. When specifying the source of recycled plastics, consideration should also be given to discriminate post-industrial recycled (PIR) plastics and post-consumer recycled (PCR) plastics. These two types of recycled plastics are very different from a polymer compositional standpoint and could have distinct impacts on the performance properties of RPM asphalt binders and mixtures.

Due to the inherent incompatibility and a large difference in the viscosity and density between recycled plastics and asphalt binder, RPM asphalt binders are susceptible to phase separation. Therefore, future research on compatibilization of recycled plastics to enhance the storage and service stability of RPM asphalt binders is needed. One such effort was initiated by FHWA for the 2020 Exploratory Advanced Research (EAR) program (FHWA, 2020). Furthermore, research efforts should also be devoted to validating the applicability of asphalt binder tests, including the standard Superpave performance grading (PG) test methods and the advanced rheological and chemical test methods commonly used in asphalt research, to RPM asphalt binders due to a concern of non-homogeneity. Future research is also needed to evaluate the chemical compatibility between recycled plastics and other additives used in asphalt binder, such as warm mix asphalt (WMA), anti-strip agent (ASA), and recycling agent (RA). If there is an incompatibility issue, the resultant RPM asphalt binders will not perform as well as anticipated and could cause premature pavement failure.

Many existing studies have indicated that adding recycled plastics increases the stiffness of asphalt binders and mixtures, which is expected to contribute to asphalt pavements with better rutting resistance. However, the increased binder stiffness, along with reduced relaxation properties, are likely to have a detrimental effect on the fatigue and cracking resistance of RPM asphalt binders and mixtures. Since durability-related cracking is now the primary form of distress in asphalt pavements in the United States, future research on the performance characterization of RPM asphalt binders and mixtures should focus more on the evaluation of fatigue and cracking resistance than rutting resistance. In order to consider the effect of asphalt aging, laboratory fatigue and cracking tests should be conducted on RPM asphalt binders and mixtures that have been long-term aged.

Future research efforts are also needed to address safety concerns for the plant production of RPM asphalt mixtures. When recycled plastics are added via the dry process, extreme caution should be exercised to ensure that they stay away from the burner-end of the drum to avoid direct contact with the burner flame. For this reason, it is preferable from an operation safety standpoint to introduce recycled plastics into the asphalt plant through the reclaimed asphalt pavement (RAP) conveyor rather than the cold feed conveyor. Furthermore, there is a safety concern that recycled plastics, especially those containing excessive fine particles, could coat and blind the filter bags in the baghouse. As a result, exhaust gases would not be able to pass through the filter bags, reducing the operation efficiency of the baghouse and increasing the opportunity for a baghouse fire.

There are major health and safety concerns about the occupational exposure of asphalt workers to hazardous air pollutants (HAPs) from the heating of recycled plastics during the production and construction of RPM asphalt mixtures. Recycled plastics, especially PCR plastics, can release HAPs including volatile organic compounds (VOCs), such as benzene, toluene, and polycyclic aromatic hydrocarbons (PAHs) when they are subjected to elevated temperatures. Therefore, research is needed to address the health effects of occupational exposure to HAPs at production and construction sites.

Asphalt pavement is the most recyclable material in the United States. This superior recyclability perspective should not be compromised with the incorporation of recycled plastics. It remains unknown whether RPM asphalt mixtures, upon completion of their service lives, can be recycled and added into new asphalt mixtures as RAP. The major concern for the lack of recyclability of RPM asphalt mixtures is the potential release of microplastics and nanoplastics from the weathering of in-service asphalt pavements and the milling of asphalt pavements after they have reached the end of their service lives. Use of ventilation and water-spray controls on asphalt pavement milling machines for silica dust controls might be able to address the release of microplastics and nanoplastics from the pavement milling operation, but their effectiveness has yet to be determined. Another major environmental concern regarding the use of recycled plastics in asphalt that needs further investigation is the leaching of phthalates, bisphenol-A (BPA), microplastics, and nanoplastics from in-service asphalt pavements. These harmful materials and pollutants not only have an adverse impact on the environment but also can cause health issues for humans and animals.

4.2 Sourcing of Recycled Plastics

- **Research is needed to specify the source and recycling process of recycled plastics for use in asphalt.**
- **Specific gravity, melting temperature, particle size, MFI, degree of crystallinity, and ash content are properties of recycled plastics that are considered important and thus, should be specified for asphalt applications.**
- **When specifying the use of recycled plastics in asphalt, consideration should be given to discriminate PIR and PCR plastics.**

There are currently no robust specifications available on the source, recycling process, and properties of recycled plastics for use in asphalt. Although the use of many different types of recycled plastics have been reported in the literature, the source and properties of these plastic materials were not characterized and reported in a consistent manner. Some of the recycled plastics used in asphalt research had gone through a systematic recycling process that consisted of collection, sorting, washing, resizing, identification, and compounding. As a result, these post-processed recycled plastics were typically made up of polymer resins with a high degree of consistency and cleanliness. However, other recycled plastics were added into asphalt binders or mixtures in an unprocessed or partially processed state. In this case, the recycled plastics typically consisted of a mix of different polymer resins and non-plastic contaminants at unknown proportions. Because each individual component of the unprocessed or partially processed recycled plastics has different physicochemical properties, they may yield RPM asphalt binders and mixtures with inconsistent quality characteristics and performance properties. Thus, there is a need to specify the source and recycling process of recycled plastics for use in asphalt binders and mixtures.

Specific gravity, melting temperature, and particle size are the three most common properties of recycled plastics reported in the literature. When recycled plastics are added via the wet process, specific gravity plays an important role in the phase separation tendency of RPM asphalt binders among other factors that affect the microstructure and compatibility of the asphalt-plastic system. For the dry process, the incorporation of recycled plastics will affect the volumetrics of RPM asphalt mixtures because of the large difference in specific gravity between recycled plastics and aggregates. Melting temperature is another important property because it is often the deciding factor as to how recycled plastics should be added into asphalt. Melting temperature can be measured using the differential scanning calorimetry (DSC). As discussed previously, the wet process is considered suitable for recycled plastics with a low melting temperature (i.e., 150 to 160°C), while the dry process is applicable to virtually all types of recycled plastics. The particle size of recycled plastics is also important because it affects the ease of blending into asphalt binders for the wet process and the aggregate gradation of asphalt mixtures for the dry process.

Other properties of recycled plastics that are considered important for asphalt applications via the wet process include, but are not limited to, MFI, degree of crystallinity, and ash content. MFI is a measure of the mass of the plastic sample that is extruded through a capillary at a certain temperature and force. The standard test method for measuring MFI is ASTM D1238. MFI can be used to indicate the flow properties and molecular characteristics of different recycled plastics on a relative basis. For example, a lower MFI value indicates a relatively higher melt viscosity and the presence of longer polymer chains or greater polymer branching (Shenoy et al., 1983). Testing of MFI with different load weights could also provide information on the molecular weight distribution of the recycled plastic sample (Bremner et al., 1990). Degree of crystallinity indicates the fraction of ordered molecules and molecular chains in the recycled plastic sample, which typically ranges between 10 and 80 percent (Bassett, 1981). DSC is the most common test method for measuring the degree of crystallinity, but additional analytical techniques such as X-ray diffraction (XRD), infrared spectroscopy, and nuclear magnetic resonance (NMR) can also be used. Like many other polymers, recycled plastics with a high degree of crystallinity are generally not desired for asphalt modification because the resultant RPM asphalt binders are brittle, have poor low-temperature relaxation properties, and are susceptible to premature surface cracking. Finally, ash content should be considered because it indicates the amount of inorganic residues in the recycled plastic sample. These inorganic residues are contaminants and could be in the form of anti-block agents, fillers, reinforcements, catalyst residues, and pigments, among others (Ranta-Korpi et al., 2014). Recycled plastics with a low ash content are preferred for use in asphalt binders and mixtures.

When specifying the source of recycled plastics for use in asphalt, considerations should also be given to differentiate PIR plastics and PCR plastics. PIR plastics, also known as pre-consumer recycled plastics or manufacturing waste plastics, are generated by manufacturers and processors in the original manufacturing process. PCR plastics, on the other hand, are end products that have completed their life cycle as a consumer item. PCR plastics are usually collected by local recycling programs and processed at centralized recycling facilities for end-of-life recycling applications. Because PIR plastics have not entered the consumer market, they are free from post-consumer contaminants and are considered a "cleaner" stream than PCR plastics from a polymer compositional standpoint. It is anticipated that writing a specification on PCR plastics for use in asphalt would be more challenging than PIR plastics. However, research is needed to determine whether PIR and PCR plastics would have different impacts on the performance properties of RPM asphalt binders and mixtures, and if so, what the inherent properties of recycled plastics that cause the difference would be and how these properties should be controlled in the specification.

4.3 Methods of Incorporating Recycled Plastics

Standardization guidelines are needed to define the scope and details of the different methods of incorporating recycled plastics in asphalt.

Although the wet process and the dry process have been recognized as the two most common methods of incorporating recycling plastics in asphalt, standardization guidelines are needed to further define the scope and details of each method. For the wet process, it should be specified as to whether recycled plastics will act as asphalt modifiers or asphalt replacement. The asphalt pavement industry has a long history of using modified asphalt binders to enhance the performance of asphalt pavements. Asphalt modifiers include polymer or non-polymer additives that improve certain performance properties of asphalt binders. Recycled plastics such as PE and PP are plastomeric polymers, and thus, fall into the category of asphalt modifiers. Asphalt replacement, on the other hand, refers to additives that are added to substitute for a portion of asphalt binder without necessarily providing performance improvement. The intent of these additives is mainly to reduce the amount of asphalt binder in the mixture and consequently, provides economic benefits by lowering material costs. The literature review identified a few proprietary recycled plastic products that were claimed as asphalt replacement instead of asphalt modifiers.

For the dry process, recycled plastics will be added directly into the asphalt mixture instead of asphalt binder. In this process, recycled plastics can act as asphalt modifiers, asphalt replacement, aggregate coating, aggregate replacement, or any combination of the above. The asphalt modifier and asphalt replacement approaches are like the wet process in principle. However, because no high-shear blending will be used, recycled plastics cannot fully dissolve into the asphalt binder. As a result, recycled plastics will behave as a binary phase system where some of them exist in the asphalt binder or mortar as a quasi-continuous phase while the others contribute to the aggregate structure as a discontinuous phase. Same as the wet process, the aggregate coating approach is only applicable to recycled plastics with a melting temperature below the production temperature of asphalt mixtures. Upon mixing with the hot aggregates, recycled plastics will melt and produce plastic-coated aggregates for further mixing with the asphalt binder. The resultant mixtures will have a thin layer of recycled plastics at the asphalt-aggregate interface. On the other hand, the aggregate replacement approach is typically recommended for recycled plastics with a melting temperature above the production temperature of asphalt mixtures. In this approach, the role of recycled plastics is to contribute to the aggregate structure by replacing a portion of the fine and/or medium-size aggregate particles. Given the very different roles of recycled plastics in asphalt mixtures, a clear distinction between the aggregate coating approach and the aggregate replacement approach is needed when adding recycled plastics via the dry process.

Finally, there is a need to standardize the terminology of the dosage of recycled plastics for reporting purposes. It is recommended to specify and report the dosage of recycled plastics by weight of asphalt binder for the wet process, and by weight of aggregate for the dry process.

4.4 Laboratory Binder Characterization

Research is needed to:

- **Mitigate the phase separation of RPM asphalt binders.**
- **Evaluate the impact of recycled plastics on the fatigue and cacking resistance of asphalt binders.**
- **Verify the applicability of laboratory asphalt binder tests to RPM asphalt binders.**
- **Assess the compatibility between recycled plastics and other additives used in asphalt binders.**
- **Develop new solvent and testing technologies for RPM asphalt binders.**

Because of the inherent incompatibility and a large difference in viscosity and density between recycled plastics and asphalt binder, RPM binders are susceptible to phase separation and have poor storage and service stability. Although existing studies have identified several potential steric stabilizers or compatibilizers to improve the storage stability test results, the resultant RPM binders still exhibited phase separation after long-term storage at ambient temperatures, and thus, had a limited shelf life. Therefore, future research on compatibilization of recycled plastics to improve the stability of RPM asphalt binders is needed. In addition to the incorporation of a steric stabilizer or compatibilizer, appropriate chemical modification of recycled plastics to facilitate the formulation of polymeric materials with varying degrees of crystallinity and polarity is another potential approach to mitigate the phase separation of RPM asphalt binders. Future research is also needed to evaluate the consistency of RPM asphalt binders. Fluorescence microscopy can be a powerful analytical technique to visualize the morphology and dispersion of recycled plastics in asphalt binder. RPM asphalt binders with a uniform distribution of small-size plastic polymer particles are typically desired from a stability perspective.

There is a general agreement among existing studies that adding recycled plastics stiffens the asphalt binder, as indicated by increased softening point and viscosity as well as reduced penetration and ductility. This stiffening effect is expected to provide RPM asphalt binders with better shear resistance at high temperatures and contribute to better rutting performance of asphalt pavements. However, this same stiffening effect could also have a detrimental impact on the intermediate-temperature fatigue resistance and low-temperature cracking resistance of RPM asphalt binders because of the increased embrittlement and reduced relaxation properties. Rutting is no longer a concern for many highway agencies in the United States. Instead, durability-related cracking has become the primary form of distress governing the service life of asphalt pavements. Therefore, future research on performance characterization of RPM asphalt binders should focus more on the evaluation of fatigue and cracking resistance than rutting resistance.

Another research area in need of further investigation is to validate the applicability of laboratory asphalt binder tests to RPM asphalt binders. The standard PG test methods and many other advanced rheological and chemical test methods used in asphalt research are based on an assumption that the asphalt binder sample is in a homogeneous state. The validity of this assumption, however, remains unknown for RPM asphalt binders. Therefore, modifications to current test methods may be needed to accommodate the non-homogeneity of RPM asphalt binders. Future research efforts also need to assess the chemical compatibility between recycled plastics and other additives used in asphalt binders, such as WMA, ASA, and RA. If there is an incompatibility issue, the resultant RPM asphalt binders and mixtures will not perform as well as anticipated and could cause premature pavement failure. Finally, certain types of recycled plastics may be insoluble in solvents that are commonly used for the extraction and recovery of asphalt binders and those used in chromatography and spectroscopy characterization techniques for polymers and asphalt binders. Therefore, new solvent and testing technologies are needed to accommodate the appropriate characterization of asphalt binders containing recycled plastics.

4.5 Laboratory Mixture Characterization

Research is needed to:

- **Evaluate the impact of recycled plastics on the fatigue and cracking resistance of RPM asphalt mixtures.**
- **Quantify the potential benefits of high-modulus RPM asphalt mixtures in reducing the thickness of asphalt pavements from a structural design perspective.**
- **Identify the impact of the dry process of adding recycled plastics on the volumetric mix design and texture characteristics of asphalt mixtures.**

Similar to the previous discussions in the Laboratory Binder Characterization section (Section 4.3), further research is needed to evaluate the impact of adding recycled plastics on the fatigue and cracking resistance of RPM asphalt mixtures. Enhanced mixture durability and cracking resistance is the key to improving the performance and service life of asphalt pavements in the United States. The effect of asphalt aging should be considered when evaluating the cracking resistance of RPM asphalt mixtures. It is recommended to conduct mixture cracking tests on specimens that have been long-term aged. Asphalt mixtures showing promising cracking test results after long-term aging are more likely to perform well in the field over the long term than those tested without long-term aging. Traditional mixture long-term aging protocols require the aging of compacted specimens or loose mix in an oven at elevated temperatures ranging from 60°C to 135°C, where the duration of the aging time varies significantly from hours to weeks, mainly depending on the level of field aging targeted for. Alternatively, an Accelerated Pavement Weathering System can be used to simulate the simultaneous weathering of asphalt pavements to rain, relatively humidity, sunlight, and temperature in a laboratory environment.

Many of the existing studies revealed that adding recycled plastics increased the stiffness of asphalt mixtures and the resultant mixtures could be used for high-modulus asphalt concrete (HMAC) applications. Several researchers also suggested that this increased mixture stiffness could reduce the thickness of asphalt pavements from a pavement structure design perspective. However, this potential thickness reduction benefit of RPM asphalt mixtures has not been quantified, and thus, warrants further investigation through laboratory testing and pavement design analysis.

For the dry process of adding recycled plastics, there is a need for research to quantify the dispersion and mixing of recycled plastics with the aggregates. It remains unknown whether recycled plastics can be uniformly distributed within the asphalt mixture without getting clustered at discrete locations. The degree of dispersion of recycled plastics will affect the consistency and performance properties of RPM asphalt mixtures. Future research is also needed to determine the impact of recycled plastics on the volumetric mix design process.

Because of the large difference in specific gravity, adding recycled plastics as aggregate replacement will affect the mixture volumetrics, such as air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). Depending on the amount of recycled plastics added, the optimum asphalt binder content selected based on a target air voids (e.g., 4 percent) could also change for a given mix design. Finally, research is needed to evaluate the impact of recycled plastics on the texture characteristics of asphalt mixtures, which will affect the skid resistance and rolling resistance of asphalt pavements.

4.6 Plant Operations

- **Agitated storage tanks are needed to prevent the phase separation of terminal blended RPM asphalt binders, but they are not widely available among asphalt contractors.**
- **There are major barriers to the large-scale implementation of the plant blending approach of preparing RPM asphalt binders during mixture production.**
- **Production trials are needed to determine safe and effective methods of introducing recycled plastics into the asphalt plant using the dry process.**
- **There is a plant operation safety concern that certain recycled plastics could jeopardize the operation efficiency of the baghouse and possibly cause a baghouse fire.**
- **It remains unknown how quality assurance testing could be conducted for the dry process of adding recycled plastics during plant production.**

For the wet process, recycled plastics can be blended into the asphalt binder using either the terminal blending approach or the plant blending approach. Terminal blended RPM asphalt binders are required to have superior stability to prevent from phase separation during transportation and storage at the asphalt plant. As discussed previously, phase separation is the major challenge for adding recycled plastics via the wet process. Therefore, the quality assurance (QA) testing of terminal blended RPM asphalt binders should include the storage stability test, and the QA samples should be taken from the asphalt tank for testing at a periodic frequency. A benefit of the terminal blending approach is that no major plant modifications are needed for the production of RPM asphalt mixtures other than the installment of an agitated storage tank if it is not currently available. Use of agitated storage tanks would help eliminate the phase separation issue, but they are not widely available among asphalt contractors.

Same as the Novophalt® process, the plant blending approach requires a mobile high-shear blending unit to facilitate the on-site formulation of RPM asphalt binders at the asphalt plant during production. For this approach, because the RPM asphalt binders can be directly pumped into the plant for mixing with aggregates without the need for transportation and storage, phase separation is not as critical as for the terminal blending approach. However, the plant blending approach is not easy to implement because of the scheduling difficulty and high transportation costs of the portable blending unit. There are also concerns that the certification of plant blended RPM asphalt binders for acceptance purposes can be challenging, if not impossible, because of the high susceptibility of these binders to phase separation.

One big question regarding the dry process is how to introduce recycled plastics into the asphalt plant. Two potential points of introduction identified in the literature are the cold feed conveyor and RAP conveyor (or RAP inlet). However, the former is not recommended from a safety standpoint. The temperature of exhaust gases inside the drum can be as high as 760°C (Brown et al., 2000), which is higher than the flash point of virtually all types of recycled plastics. As recycled plastics enter and travel inside the drum, they could reach their flash point and ignite upon contact with the burner flame, causing explosions at the asphalt plant. Therefore, it is recommended to introduce recycled plastics through the RAP conveyor so that they can stay away from the burner-end of the drum mixer or the dryer drum and avoid direct contact with the burner flame during the production process.

Another question that needs to be addressed through further investigation is whether recycled plastics can uniformly coat the surface of aggregate particles when they are added using the aggregate coating approach within the dry process. Questions like, “does the mixing time need to be extended and mixing temperature increased to account for the relatively higher viscosity of recycled plastics relative to asphalt binder?” need to be answered. Furthermore, there is a plant operation safety concern that recycled plastics, especially those containing excessive fine particles, could possibly coat and blind the filter bags in the baghouse. As a result, the exhaust gases will not be able to pass through the filter bags, which jeopardizes the operation efficiency of the baghouse and increases the opportunity for a baghouse fire. Finally, it remains unknown how the QA testing could be conducted for the dry process of adding recycled plastics. Similar to the dry process of adding ground tire rubber (GTR), state highway agencies may find it challenging to verify the amount of recycled plastics added into the asphalt mixture during production. A potential approach is to use electronic weigh systems with ticket printouts as those currently used to introduce fibers, lime, fly ash, and other dry additives during plant production, but their effectiveness and accuracy in feeding the right amount of recycled plastics needs to be verified through trial projects.

4.7 Construction

Field demonstration projects are needed to identify the potential changes in the construction practice of asphalt mixtures containing recycled plastics.

Workability and compactability of asphalt mixtures are important factors in ensuring the good performance of asphalt pavements. They are dependent upon the viscosity of asphalt binder, aggregate gradation, and asphalt binder content, among other factors. Because recycled plastics will affect the viscosity of asphalt binder when added via the wet process and possibly the aggregate gradation (in a much less degree though) when added via the dry process, they could affect the workability and compactability of RPM asphalt mixtures. Therefore, research is needed to assess the significance of this impact through laboratory evaluations. In the United States, many WMA additives are being widely used as compaction aids to help achieve proper in-place density during construction. Thus, consideration should be given to the compatibility between recycled plastics and WMA additives when evaluating the compactability of RPM asphalt mixtures. A key question that needs to be answered is “can WMA additives accommodate the use of recycled plastics in asphalt mixtures in terms of providing the anticipated benefits of reducing mixture production temperature and improving field compaction?” In addition to laboratory evaluation, low-risk demonstration projects are also needed to identify the potential changes in the construction practice of asphalt mixtures containing recycled plastics. These projects will also provide an opportunity to determine whether extra maintenance activities and cost for the paving equipment would be needed for the construction of RPM asphalt mixtures.

4.8 Health and Safety

There are significant health and safety concerns about the occupational exposure of asphalt workers to HAPs and PFASs from the heating of recycled plastics during plant production and construction.

There are significant health and safety concerns about the occupational exposure of asphalt workers to HAPs from the heating of recycled plastics during the production and construction of RPM asphalt mixtures. Recycled plastics, especially PCR plastics, typically contain chemical additives that were added in the manufacturing process as well as contaminants and deleterious materials that they were exposed to during the use phase. Some of these recycled plastics can release HAPs including PAHs and VOCs when subjected to elevated temperatures (Chin and Damen, 2019). Therefore, research is needed to evaluate the health effects of occupational exposure to HAPs from the production and construction of asphalt mixtures containing recycled plastics.

In addition to traditional HAPs, the potential presence of contaminants of emerging concern, per- and polyfluoroalkyl substances (PFASs), has also raised health and safety concerns regarding the use of certain types of recycled plastics in asphalt. These plastics are primarily limited to polytetrafluoroethylene (PTFE) and other fluorinated polymers and their usage has declined substantially in recent years. PFASs are synthetic organofluoride chemical compounds and are considered persistent organic pollutants with a serum elimination half-life of four to five years (Hogue, 2019). Although short-term exposure to a low level of PFASs is not likely to cause adverse health effects, the accumulation of these substances in humans over time could lead to adverse health outcomes such as hypercholesterolemia, ulcerative colitis, thyroid disease, cancer, and pregnancy-induced hypertension and pre-eclampsia (EPA, 2020). Therefore, future work is needed to evaluate the health and safety effects of worker exposure to PFASs in recycled plastics.

Finally, as previously discussed in the Plant Operations section (Section 4.6), the dry process of adding recycled plastics has safety concerns from a plant operating standpoint. Further field evaluation efforts at asphalt plants are needed to ensure that recycled plastics would not have direct contact with the burner flame inside the drum mixer or dryer drum to cause fire and explosions, nor jeopardize the operation efficiency of the filter bags and cause fire in the baghouse.

4.9 Environmental Impact

- **Research is needed to evaluate and verify the recyclability of RPM asphalt mixtures.**
- **There are major environmental concerns about the potential release of microplastics and nanoplastics as well as the leaching of harmful materials and pollutants from asphalt pavements containing recycled plastics.**
- **Research is needed to establish upstream LCA data for asphalt pavements containing recycled plastics.**

Asphalt pavement is the most recyclable material in the United States. According to the latest asphalt pavement industry survey by NAPA, more than 97

percent of asphalt mixtures reclaimed from existing asphalt pavements in 2018 were put back to use in new pavements and the remaining 3 percent was used in other civil engineering applications (Williams et al., 2018). The recyclability characteristics of asphalt pavements must be maintained with the incorporation of any type of recycled materials, including recycled plastics. However, it remains unknown whether RPM asphalt mixtures can be successfully recycled and added into new asphalt mixtures as RAP upon completion of their service lives. If the recyclability can be proved feasible, RPM asphalt mixtures, especially those containing PE, may yield better quality RAP materials than those containing other types of polymers because PE is more resistant to ultraviolet radiation and oxidation due to its inertia nature. Nevertheless, this topic has not been investigated in existing literature and warrants further research.

There is a major environmental concern about the potential release of microplastics and nanoplastics from the weathering of in-service asphalt pavements containing recycled plastics and the milling of asphalt pavements after they have reached the end of their service lives. Plastics have a tendency to break into small particles upon impact and these small plastic particles are often known as microplastics and nanoplastics (Chin and Damen, 2019). According to the U.S. National Oceanic and Atmospheric Administration (NOAA), microplastics are any type of plastic fragment that is less than 5 mm in length (Arthur et al., 2009). The definition of nanoplastics is still under debate, but they typically refer to very small plastic particles with an upper size of 100 to 1000 nm (Gigault et al., 2018). Not only are microplastics and nanoplastics a major threat to marine life, they can also negatively affect the growth of plants and earthworms and human health (Wikipedia, 2020). Use of ventilation and water-spray controls on asphalt pavement milling machines for silica dust controls might be able to address the release of microplastics and nanoplastics from pavement milling operations, but their effectiveness has yet to be determined through future research and field trials.

Leaching of harmful materials and pollutants such as phthalates, BPA, and microplastics from asphalt pavements made of RPM asphalt mixtures is another environmental concern regarding the use of recycled plastics in asphalt. Phthalates and BPA are two types of man-made chemicals used in many daily use plastic products, especially PET plastic bottles. There is scientific evidence that phthalates and BPA may cause a variety of health issues for humans and animals, such as hormonal and developmental problems (NIEHS, 2018; NIEHS, 2020). Therefore, there is a need to evaluate the leaching of phthalates and BPA from asphalt mixtures modified with recycled PET, as well as the leaching of microplastics and nanoplastics from other types of RPM asphalt mixtures.

When recycled plastics are added via the wet process, the resultant RPM asphalt binder will likely have a higher viscosity than the base binder and thus, may require higher production and construction temperatures to maintain adequate workability and compactability of the mixture. However, the elevated temperatures will increase the emissions of PAHs, VOCs, total organic compounds (TOCs), and objectional odors, which have a negative impact on the environment and increase the occupational exposure of asphalt workers to HAPs. Therefore, emissions measurement, monitoring, and analysis at the production and construction sites of RPM asphalt mixtures are needed. Finally, life cycle assessment (LCA) plays an important role in the asphalt pavement industry toward reducing the impacts of pavement systems on humans and the environment, as well as identifying potential unintended negative consequences (Harvey et al., 2014). Thus, research efforts should be devoted to establishing upstream LCA data for asphalt pavements containing recycled plastics and comparing its environmental impact and sustainability benefits against other potential recycling applications for waste plastics. FHWA has an ongoing research study on the LCA of asphalt pavements with recycled plastics. Preliminary findings of the study can be accessed elsewhere (Rangelov et al., 2020).

4.10 Field Performance

Long-term pavement performance data is needed for field projects constructed using RPM asphalt mixtures.

Although a large number of field projects using RPM asphalt mixtures have been constructed, the long-term pavement performance data for many of these projects is not available. Such performance data is of extreme importance to intuitively quantify the impact of recycled plastics on the service life of asphalt pavements, which also provides an indispensable input for the life cycle cost analysis (LCCA) of RPM asphalt mixtures. Therefore, it is recommended for future research to establish a pavement performance database for RPM asphalt mixtures, which should take into consideration field projects with different pavement ages, roadway classifications, traffic levels, climate regions, and underlying pavement structures. To enhance the value of the database, field performance data should be collected and analyzed in a consistent and objective manner, preferably following the guidelines of federal or state highway agencies.

4.11 Other Potential Applications

In addition to asphalt pavements, future research is needed to explore the use of recycled plastics in other civil engineering applications. For example, because of the low density, recycled plastics have the potential of being used as alternative lightweight backfill materials for embankments and landscape projects where natural fill materials are not available. Furthermore, the aggregate replacement approach under the dry process of adding recycled plastics may also be applicable to aggregate base courses, where potentially a larger amount of recycled plastics could be used if they can provide adequate structural support under traffic and are not susceptible to the leaching of microplastics, nanoplastics, and other deleterious materials. Similarly, recycled plastics could also be used to replace aggregates and fillers for cold asphalt recycling and Portland cement concrete applications.

5 CONCLUDING THOUGHTS

While significant effort has gone into understanding the impacts of recycling plastics in asphalt, more research is required by the asphalt, plastics, and petrochemical industries in order to advance the infrastructure of low-cost recycling of plastics.

There is no silver bullet, but patience, partnership, and open communication are essential to determine if plastic in asphalt can be the next great recycling story.

Right now, patience is of most importance. Research takes time and rushing plastic for political reasons (e.g., RTR) or for economic reasons (e.g., RAS) is not optimal. Remember that it has taken 40 years to get a national average of 21 percent RAP in asphalt mixtures. NCHRP 9-66 is to focus on plastics use in asphalt. FHWA is sponsoring research on plastic-binder compatibility. TxDOT is conducting research on the subject, and states and private owners are starting to conduct demonstration projects. Time should be given to these, and other, projects to decide if/how/when recycling plastics in asphalt makes sense.

The asphalt industry, the plastic industry, academia, and road owners need to partner on ways to move forward responsibly toward delivering safe, durable, and sustainable pavements to the driving public. Communication is critical to ensure the public understands our current recycling efforts. Throughout this process, openness is important. Yes, plastic was incorporated in the past and worked to varying levels. However, the market has changed considerably since, and today's market factors may be suitable for plastic. India uses plastic for mixture modification via a dry process, and France uses plastic in its high modulus asphalt mixtures. However, coming full circle, patience is needed for partner driven research to evaluate plastics' worthiness in conventional asphalt mixtures. We should avoid saying "This isn't going to work,", but rather we should try to answer the questions that will help everyone understand the true viability of plastics in asphalt. If plastics are to be used in asphalt mixtures, they must be safe to use, recyclable, cost effective, and provide equivalent or improved service life. If academia, industry, and agencies work together to ensure these requirements, then asphalt is not a viable end-market opportunity for recycling plastic waste.

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