NCHRP Project 9-66
Interim Report

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

Performance Properties of Laboratory Produced Recycled Plastic Modified (RPM) Asphalt Binders and Mixtures

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ABCD	Asphalt Binder Cracking Device
AfPA	Australian Flexible Pavement Association
ASA	Anti-strip Agent
ATR	Attenuated Total Reflection
BBR	Bending Beam Rheometer
BPA	Bisphenol A
BYET	Binder Yield Energy Test
CMU	Chiang Mai University
CO_2	Carbon Dioxide
CTM	Circular Texture Meter
DFT	Dynamic Friction Tester
DSC	Differential Scanning Calorimetry
DSR	Dynamic Shear Rheometer
DTG	Derivative Thermogravimetry
DWT	Dongre Workability Test
E*	Dynamic Modulus
EAR	Exploratory Advanced Research
EPA	Environmental Protection Agency
EVA	Ethylene-vinyl Acetate
FHWA	Federal Highway Administration
FN	Flow Number
FTIR	Fourier Transform Infrared Spectroscopy
GC	Gas Chromatography
GPC	Gel Permeation Chromatography
G-R	Glover-Rowe Parameter
$G\text{-}R_m$	Mixture Glover-Rowe Parameter
HAPs	Hazardous Air Pollutants
HDPE	High-density Polyethylene
HWTT	Hamburg Wheel Tracking Test (HWTT)
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
LAS	Linear Amplitude Sweep

LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LDPE	Low-density Polyethylene
LLDPE	Linear Low-density Polyethylene
MFI	Melt Flow Index
MnROAD	Minnesota Road Research Facility
MSCR	Multiple Stress Creep Recovery
MSW	Municipal Solid Waste
MTD	Mean Texture Depth
NAPA	National Asphalt Pavement Association
NAWS	NCAT Accelerated Weathering System
NCAT	National Center for Asphalt Technology
NMR	Nuclear Magnetic Resonance
NO	Nitrogen Oxide
NOAA	National Oceanic and Atmospheric Administration
NSU	National University of Singapore
PAHs	Polycyclic Aromatic Hydrocarbons
PAV	Pressure Aging Vessel
PC	Polycarbonate
PCR	Post-consumer Recycled
PE	Polyethylene
PET	Polyethylene Terephthalate
PFASs	Per- and Polyfluoroalkyl Substances
PIR	Post-industrial Recycled
PMLC	Plant-mixed, Lab-compacted
PP	Polypropylene
PPA	Polyphosphoric Acid
PS	Polystyrene
PU	Polyurethanes
PVC	Polyvinyl Chloride
QA	Quality Assurance
RA	Recycling Agent
RAP	Reclaimed Asphalt Pavement

RAS	Recycled Asphalt Shingle
RET	Reactive Elastomeric Terpolymer
RMP	Recycled Plastic Modified
rPE	Recycled Polyethylene
RTR	Recycled Tire Rubber
SAR-AD™	Saturates, Aromatics, Resins-Asphaltene Determinator
SBS	Styrene-butadiene-styrene
SEM	Scanning Electron Microscope
SIP	Stripping Inflection Point
SO_2	Sulphur Dioxide
TCB	Trichlorobenzene
TGA	Thermogravimetric Analysis
TOCs	Total Organic Compounds
TPOR	Transpolyoctenamer
TWPD	Three Wheel Polishing Device
VOCs	Volatile Organic Compounds
VTRC	Virginia Transportation Research Council
WMA	Warm Mix Asphalt
XRD	X-ray Diffraction

1. INTRODUCTION

1.1 Background

The asphalt pavement industry has a long history of using recycled materials in asphalt mixtures to achieve engineering, economic, or environmental benefits. Besides reclaimed asphalt pavement (RAP) being recycled at a rate of approximately 94 percent (Williams et al., 2019), other recycled materials such as recycled asphalt shingles (RAS), recycled tire rubber (RTR), waste engine oils, steel slag, and recycled glass have been and will continue to be used in some markets or applications.

The use of plastics in asphalt is not a new concept. The first reported use dates to the 1970s in Europe, where high-density polyethylene (HDPE) was used in Gussasphalt for pourable asphaltic mixture applications (Bardesi et al., 1999). During the 1990s, considerable research and development (R&D) efforts and field trials were devoted to a proprietary plastic modified asphalt product marketed under the trademark Novophalt®. This product required a mobile high-shear blending unit (Figure 1) at asphalt plants to blend low-density polyethylene (LDPE), and styrene-butadiene-styrene (SBS) in later formulations, with asphalt binders just prior to mix production. Although Novophalt® was demonstrated on projects in nearly 20 countries, it did not gain widespread acceptance into mainstream practice due to limited material availability, transportation costs, difficulties with on-site scheduling of blending equipment, and field performance issues. In the meantime, Polyphalt® was developed, which utilized a steric polymer stabilizer to mitigate the phase separation of polyethylene modified asphalt binders (Harbinson and Remtulla, 1994). Although this product showed promising laboratory results, it was not a commercial success due to economic and performance limitations (i.e., cracking issues).

Figure 1. Novophalt® High Shear Blending Unit

In late 2016, media reports began suggesting the use of recycled plastics in asphalt as an opportunity to improve the performance of asphalt pavements while eliminating the growing amount of waste plastics being landfilled or polluting the environment. This idea was spearheaded by the plastics industry after China and India imposed import prohibition policies on waste plastics. Since then, the plastics industry has been actively exploring new end market opportunities for over 30 million tons of waste plastics generated every year (EPA, 2018). One of the potential applications identified is asphalt pavements, while others include plastic composites, concrete, and wood composites, among others (PLASTICS, 2018). Use of recycled plastics in asphalt can be challenging due to variations in composition and the presence of non-plastic contaminants. To ensure the quality of asphalt mixtures containing recycled plastics, requirements are needed to specify the key properties of these materials and how they should be used to improve the overall pavement life cycle benefits while protecting the environment. Furthermore, post-industrial recycled (PIR) plastics and post-consumer recycled (PCR) plastics are likely to differ in composition, consistency over time, amount of contaminates, and degradation potential.

There are two main approaches for incorporating recycled plastics into asphalt mixtures: the wet process and the dry process. In the wet process, recycled plastics are added into the asphalt binder as a polymer modifier or asphalt replacement using mechanical mixing at high temperatures to produce a reasonably homogeneous recycled plastic modified (RPM) binder. One of the primary challenges of wet process RPM binder is the tendency for the plastic to separate in tanks due to differences in specific gravity, phase, and/or chemical incompatibility with the asphalt binder. In the dry process, recycled plastics are added directly into the mixture as either aggregate replacement, mixture modifier, binder modifier, or a combination thereof. National Asphalt Pavement Association (NAPA) publication IS-142 suggests that the wet process is commonly used for recycled plastics with a low melting point in the 105 to 150°C temperature range, such as LDPE and HDPE, while the dry process is applicable to virtually all types of recycled plastics except for polyvinyl chloride (PVC) due to the concern of hazardous chlorine-based dioxin emissions (Willis et al., 2020; Yin et al., 2020). The dosage of recycled plastics varies from approximately 1.0 to 12.0 percent by weight of asphalt binder for the wet process and varies from approximately 0.2 to 6.0 percent by weight of aggregate for the dry process.

Most of the existing studies on the dry process have used the Marshall stability test to evaluate the impact of recycled plastics on the properties of asphalt mixtures and found that RPM mixtures had higher Marshall stability than control mixtures (Khurshid et al., 2013; Aschuri and Woodward, 2010). Because of this observation, some researchers suggested that adding recycled plastics could extend the service life of asphalt pavements due to enhanced rutting resistance. Such conclusions lack validity since the Marshall stability has a poor correlation with field rutting performance and it ignores the fact that service life of asphalt pavements also depends on cracking performance. Only a few studies assessed the cracking and moisture resistance of RPM asphalt mixtures, but they did not yield consistent conclusions. A study in Europe showed that adding HDPE resulted in excessive hardening and contraction of asphalt binders during cooling (Bredael, 1993).

There is still a lack of understanding as to how recycled plastics interact with asphalt binder and aggregates in asphalt mixtures using the dry process. Questions such as “does the plastic coat the aggregate, become part of the asphalt binder, act as an aggregate, or act as a reinforcement similar to fibers?” need to be answered. Furthermore, it remains unknown how recycled plastics affect volumetric properties, workability, and surface characteristics of asphalt mixtures. Finally, no comprehensive research has yet been published on how recycled plastics impact the long-term performance, life-cycle costs, health and safety of asphalt workers, environmental impact, and recyclability of asphalt pavements.

1.2 Research Objective

The overall objective of NCHRP project 09-66 is to evaluate the impact of PCR plastics on the performance properties of RPM asphalt mixtures when they are added using the dry process. Specifically, this project seeks to:

1) Evaluate the rutting, cracking, moisture, and aging resistance of RPM asphalt mixtures using well-established mixture performance test methods.
2) Determine the impact of PCR plastics on volumetric properties and surface friction and texture characteristics of asphalt mixtures.
3) Assess the impacts of recycled plastics on mix production, process control, workability, and constructability of asphalt mixtures.
4) Develop a laboratory procedure for adding PCR plastics to simulate the production of RPM mixtures at asphalt plants.
5) Characterize the mingling of PCR plastics with asphalt binders in the dry process and their impacts on the rheological and chemical properties of asphalt binders extracted and recovered from RPM asphalt mixtures.
6) Provide guidance on the selection of PCR plastics for use in asphalt via the dry process.

2. LITERATURE REVIEW

A comprehensive literature review was conducted on the use of recycled plastics in asphalt binders and mixtures. This review was built upon the previous literature review efforts conducted at the National Center for Asphalt Technology (NCAT) (Yin et al., 2020), which included over 150 research reports, journal articles, trade publications, newsletter and magazine articles, technical guidance, and personal email communications. It should be noted there is likely more literature available on this topic, but they are in languages other than English and Spanish; thus, they were not included in this literature review. Figure 2 through Figure 6 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 used, method of incorporating recycled plastics into asphalt, and scope of the study. Approximately 75 percent of the literature was published within the last decade (i.e., from 2011 to 2021). The six countries with the most literature documents are United States, India, Australia, China, Malaysia, and Canada. Polyethylene (PE), including linear low-density polyethylene (LLDPE), LDPE, and HDPE, are the most studied types of recycled plastic for use in asphalt, followed by polyethylene terephthalate (PET) and polypropylene (PP), respectively. Roughly 50 percent of the literature added recycled plastics into the asphalt binder via the wet process (including Novophalt® and Polyphalt®) and approximately 32 percent used the dry process of adding recycled plastics into the mixture. Only a few studies reported the use of asphalt-plastic emulsion and plastic synthetic binder for adding recycled plastics. Regarding the scope of the study, over 85 percent of the literature focused on laboratory testing and/or field projects of RPM asphalt binders and mixtures, while the rest provided a literature review, cost analysis, pavement design, production information, accelerated pavement testing, technical guidance, environmental impact assessment, or agency specifications.

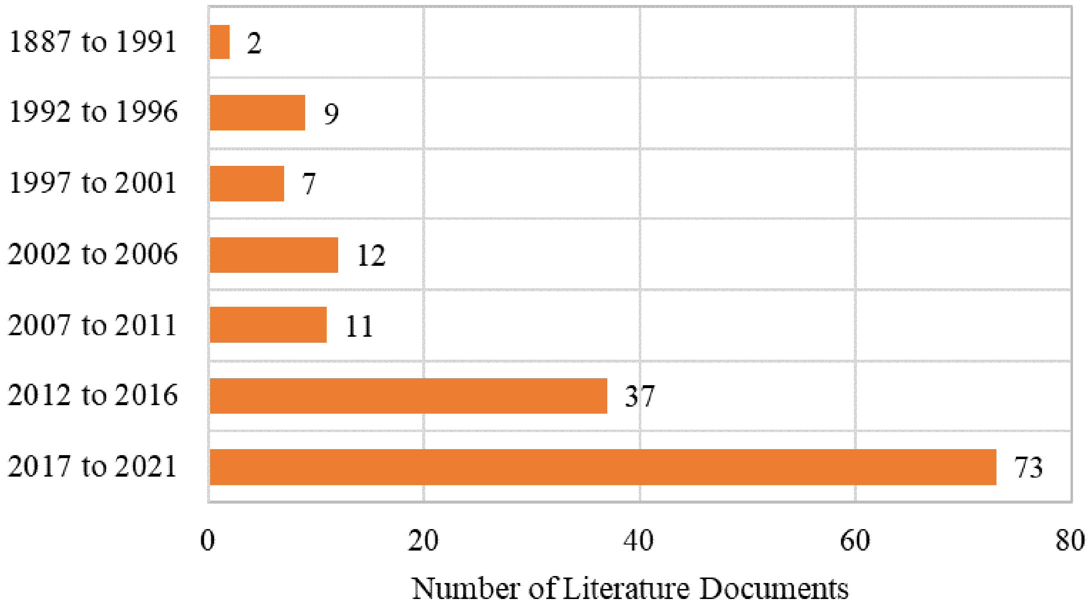


Figure 2. Classification of Literature Documents based on Publication Year

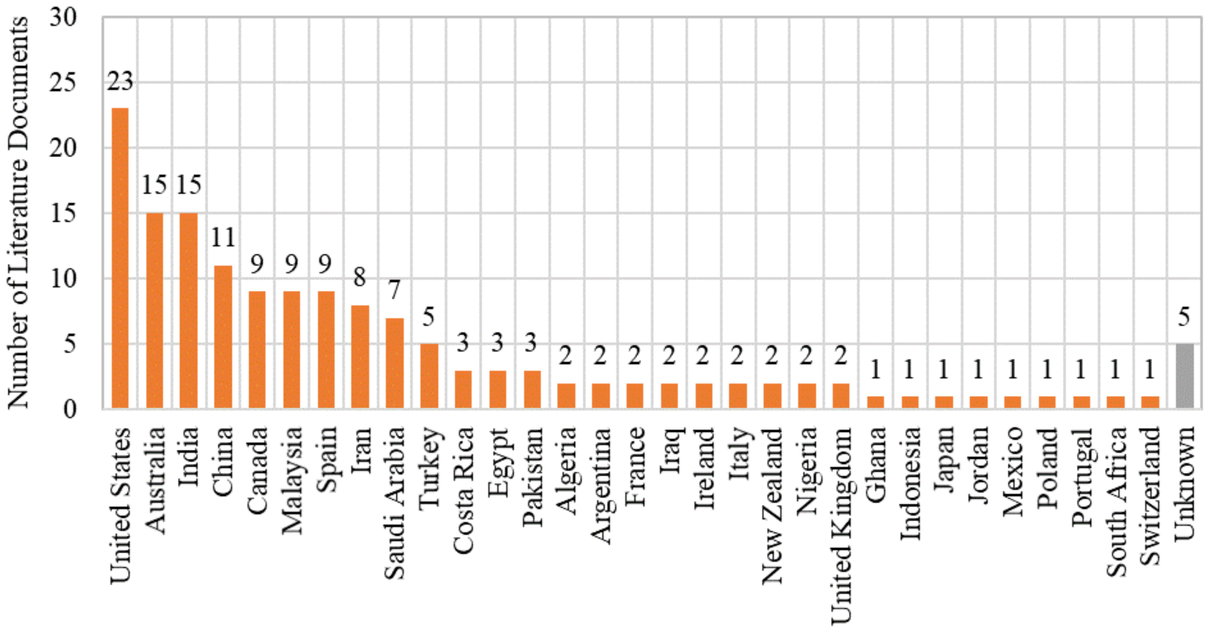


Figure 3. Classification of Literature Documents based on Place of Publication

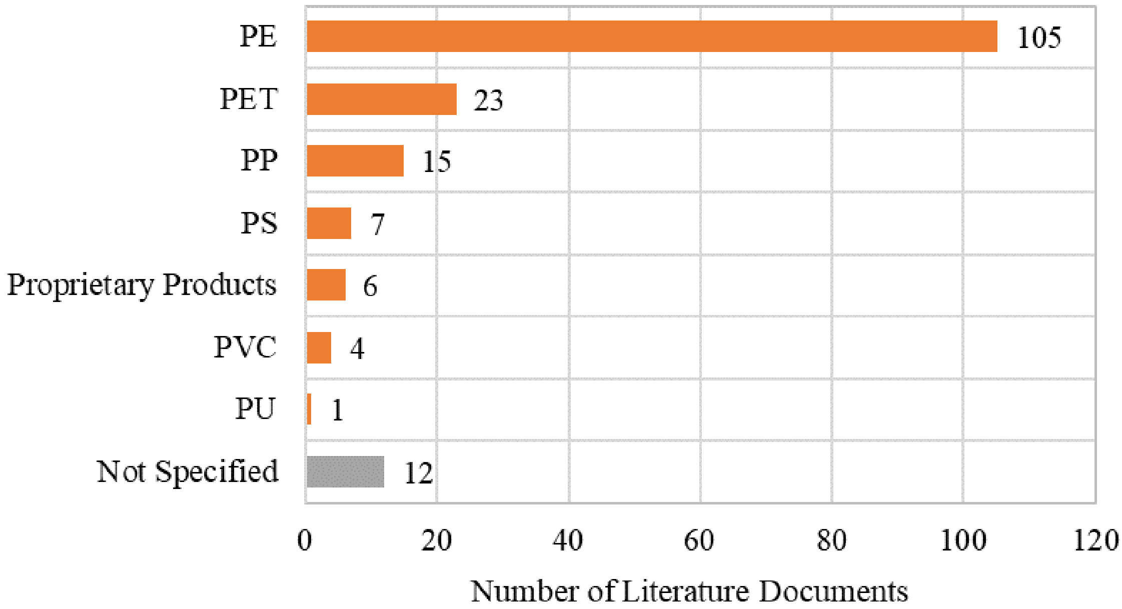


Figure 4. Classification of Literature Documents based on Type of Recycled Plastics

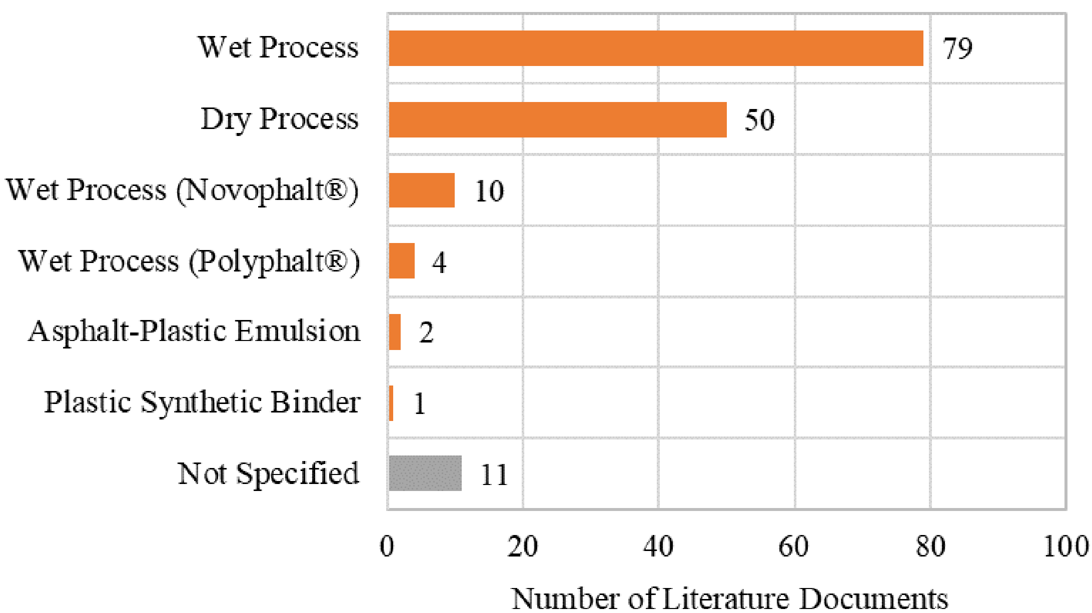


Figure 5. Classification of Literature Documents based on Methods of Incorporating Recycled Plastics

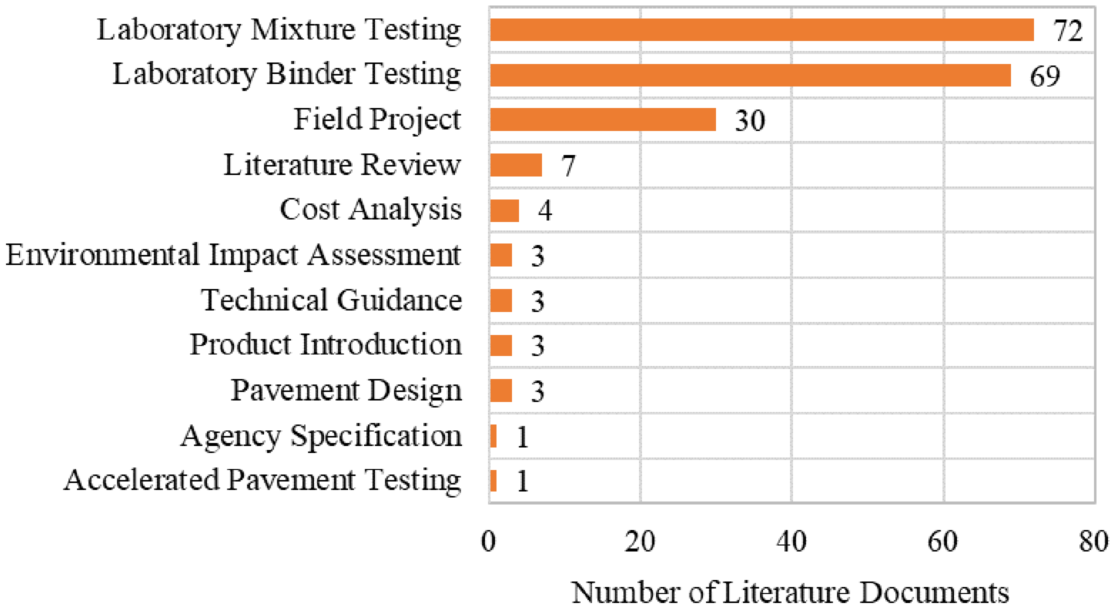


Figure 6. Classification of Literature Documents based on Scope of the Study

The following sections present a summary of literature review findings and knowledge gaps organized by topic. For each document included in the literature review, a summary table and a synthesis are provided in Appendix A of this report.

2.1 Availability and Sourcing of Recycled Plastics

2.1.1 Summary of Findings

According to the United States Environmental Protection Agency (EPA), approximately 35.7 million tons of waste plastics were generated in 2018, which accounted for 12.2 percent of municipal solid waste (MSW) generation (approximately 292 million tons) (EPA, 2021). Figure 7 presents the breakdown by plastic type in MSW based on EPA data in 2017. As shown, PP is the most common type of MSW plastic at 32.1 percent followed by PE at 29.2%. Other major types of MSW plastics include PET, PS, and PVC. Although plastics exist in all major MSW categories, the containers and packaging category has the most plastic tonnage; this category includes bags, sacks, and wraps; other packaging; PET bottles and jars; HDPE natural bottles; and other containers. Among the MSW plastics generated in 2018, only 3.1 million tons were recycled (corresponding to a recycling rate of 8.7 percent), 5.6 million tons were combusted with energy recovery, and the rest was landfilled. As shown in Figure 8, the tonnage of recycled MSW plastics increased steadily over the last four decades, with 20,000 tons in 1980 and 3.1 million tons in 2018. The recycling rate of MSW plastics also showed a steady increase over the same period, reaching a record high of 9.0 percent in 2015. This recycling rate, however, varies significantly among the different types of plastics. Based on the data provided by the Association of Plastic Recyclers, PET bottles and jars as well as HDPE natural (i.e., white translucent) bottles had a significantly high recycling rate of approximately 30 percent in 2018 (EPA, 2020).

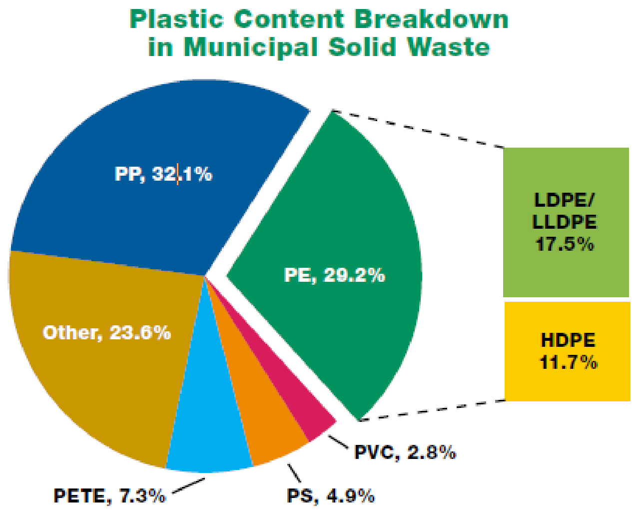


Figure 7. MSW Plastic Breakdown by Plastic Type (DuBois, 2020)

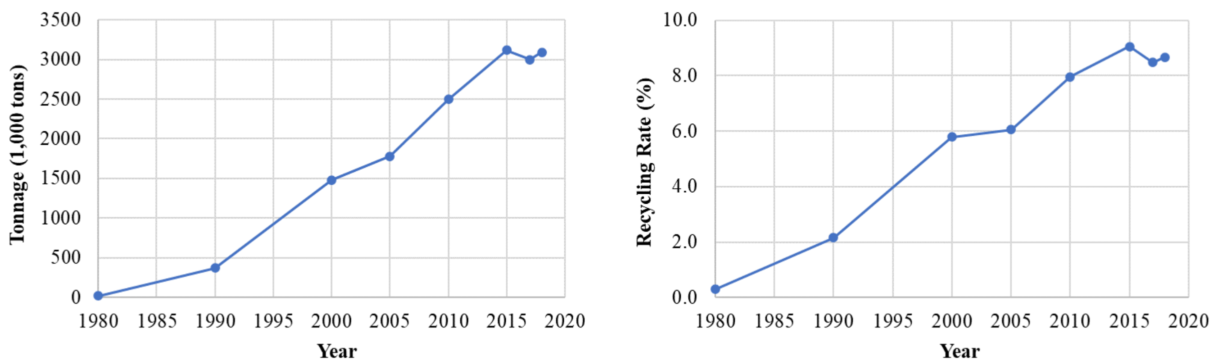


Figure 8. Tonnage (left) and Recycling Rate (right) of Recycled MSW Plastics from 1980 to 2018 (EPA, 2021)

Plastic recycling starts with the collection of PCR plastics and PIR plastics, which are also known as manufacturing waste plastics. PCR plastics are end products that have completed their life cycle as a consumer item, and are often referred to as a “dirty” plastic stream due to contamination with other non-plastic materials. PCR plastics are typically collected by local recycling programs and then processed at centralized recycling facilities for end-of-life recycling applications. PIR plastics, on the other hand, are generated by manufacturers and processors in the original extrusion or molding process. Because PIR plastics have not entered the consumer market, they are free from post-consumer contaminants and are considered a “clean” plastic stream from a polymer compositional standpoint, which requires significantly less processing efforts for recycling than PCR plastics.

In general, the recycling process of PCR plastics includes collecting, sorting, shredding, washing, decontamination, resizing, identification, and compounding. More specifically, this process starts with sorting the collected PCR plastics according to plastic type. Sorting can be done either manually or with machines equipped with automated plastic recognizing and sorting technology. After being sorted into different plastic types, the PCR plastics are then processed through a series of shredders to create plastic flakes. The shredded plastic pieces are then washed to remove dirt and contaminants that can be separated in water due to density differences. In some cases, chemicals, detergents, disinfectants, or other products are added in water to improve the cleaning and separation efficiency. Because PCR plastics can contain chemical or biological contaminants, standards have been established to regulate the reuse of PCR plastics that could have been in contact with food. Therefore, an additional step may be added 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 their properties. Separation properties typically include density, air classification, melting point, and color. In many cases, the plastics are then compounded into a new form, with the most common one being pellets. There are also other processes which directly pelletize without producing flakes as a first step. The cost of post-processed PCR plastics is highly dependent on the recycling process; the more processing that is required, the higher the cost. The cost of post-processed PCR plastics on the market can vary from $50 to $1,500/ton. The upper end of this range is for prime quality, high-end packaging applications where recycled content is desired. The level of quality is not necessary for use in asphalt pavements.

Specific gravity, melting temperature, and particle size are the three most common properties of recycled plastics reported for asphalt applications 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 that can be used to determine how recycled plastics should be added into asphalt. In general, recycled plastics with a low melting temperature (i.e., below 160°C) are suitable for use in the wet process, while most types of recycled plastics can be used in the dry process, except PVC due to safety concerns of hazardous chlorine-based dioxin emissions. The particle size of recycled plastics is also important as it affects the rate of heat transfer and thus the ability of recycled plastics to be melted and blended into asphalt binders for the wet process, and the shape and/or phase of the plastic and how that interacts with the binder and aggregate when mixing in the dry process.

In addition to specific gravity, melting temperature, and particle size, other properties of recycled plastics that are considered important for asphalt applications, especially those via the wet process, include melt flow index (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). Differential scanning calorimetry (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 content 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.

An ongoing research study at RMIT University (Melbourne, Australia) provided recommendations for the selection of recycled plastics for asphalt applications (Guppy and Giustozzi, 2021). As shown in Figure 9(a), the selection criteria include bendability, purity, storage stability, solubility, processability/easy QC test, polarity, organics contamination, and screening for “risky” additives. For each evaluation criterion, the corresponding laboratory test or analysis method was provided. Figure 9(b) shows an example of the evaluation results for different types of virgin and recycled plastics. Although these evaluation criteria appear reasonable, their robustness, effectiveness, and practicability for implementation are yet to be determined.

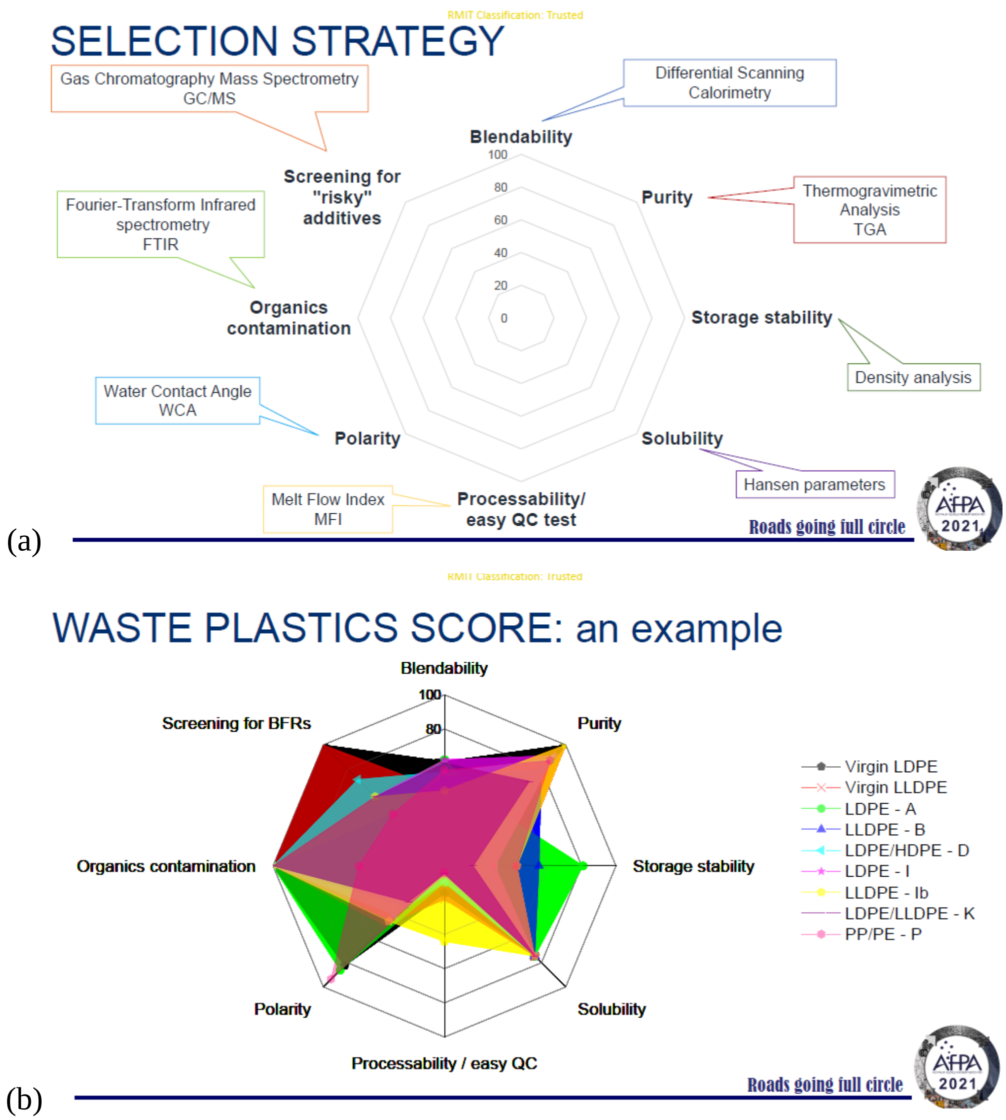


Figure 9. Recommendations for Selecting Recycled Plastics for Asphalt Applications; (a) Selection Criteria, (b) Criteria Evaluation Example (Guppy and Giustozzi, 2021)

2.1.2 Knowledge Gaps

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 the plastic materials studied 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 recycled 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 finished product source or overall polymer composition (like PE-rich or PE/PP 3:1, for example) and recycling process of recycled plastics for use in asphalt binders and mixtures.

Research is needed to evaluate whether compositional and contaminant differences in PIR and PCR plastics could significantly affect performance properties of RPM mixtures, and if so, what criteria should be used in the specification.

2.2 Methods of Incorporating Recycled Plastics

2.2.1 Summary of Findings

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 a polymer modifier or an asphalt replacement (in some cases, erroneously referred to as asphalt extenders). This requires mechanical mixing to achieve and maintain 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 1 to 12 percent by weight of asphalt binder. This dosage corresponds to about 1 to 12 lbs. of recycled plastics in a ton of asphalt mixture.

In the dry process, recycled plastics are added directly into the mixture as either an aggregate replacement, mixture modifiers, binder modifiers, or any combination of these. 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 appears to be applicable to most types of recycled plastics (e.g., PE, PP, PET, PP, PS, and others) except for PVC due to the concern of hazardous chlorine-based dioxin emissions. Several studies claimed that when recycled plastics with melting points below the mixture production temperature (e.g., LLDPE, LDPE, and HDPE) were added via the dry process, the plastics melted upon mixing with the hot aggregates and produce plastic-coated aggregates that had improved physical and surface characteristics. 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 aggregate particles while the rest was dispersed in the asphalt mortar phase. For the dry process, the dosage of recycled plastics commonly reported from approximately 0.2 to 6.0 percent by weight of aggregate, corresponding to about 4 to 120 lbs. of recycled plastics per ton of asphalt mixture. The equipment commonly used for feeding fibers into a continuous mix plant are well suited for feeding pelletized recycled plastics for the dry process.

Some studies suggest that the wet process may be economically advantageous for recycling plastics compared to traditional polymer modified binders since the recycled plastics cost less than commonly used asphalt polymers. However, there are some handling challenges with the wet process due to the potential for separation of the plastic in the binder which may require continuous agitation of the plastic modified binder, the addition of a stabilizing or comptatibilization agent, or the requirement that the plastic modified binder be used immediately after blending. The dry process has a lower cost of addition, but the interactions of the plastics with the binder and aggregates are not well understood. One study noted that the wet process has greater potential than the dry process because of its advantages in structural performance, environmental impact, safety, and life-cycle cost.

2.2.2 Knowledge Gaps

Although wet and dry processes have both been used for incorporating recycling plastics in asphalt, guidelines are needed to further define the details of each method. For the wet process, information is needed as to whether each type of recycled plastic will act as an asphalt modifier 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 an economic benefit by lowering material costs. A few proprietary recycled plastic products claim to replace rather than modify asphalt binder.

For the dry process, recycled plastics are not added to the binder, but instead are added directly into the drum or pugmill at the hot-mix plant. In this process, recycled plastics could act as asphalt modifiers, asphalt replacement, an aggregate coating, an aggregate replacement, or any combination of these. The asphalt modifier and asphalt replacement approaches are like the wet process in principle. However, because high-shear blending is not used and because of short mixing times, it is unlikely that recycled plastics will fully dissolve into the asphalt binder. As a result, recycled plastics may behave as a multi-phase system where some of the plastic melts and becomes part of the asphalt binder or mortar, some may coat the aggregate, and some may remain solid as part of the aggregate matrix. The aggregate replacement approach is considered applicable for recycled plastics that have 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 without disrupting shear strength. Given the very different roles of recycled plastics in asphalt mixtures, a closer examination of the aggregate coating concept and the aggregate replacement approach is needed. For the dry process, research is also needed to assess the dispersion of recycled plastics within the mixture for both lab and plant produced samples. The degree of dispersion will affect the consistency and performance properties of RPM asphalt mixtures.

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

2.3 Laboratory Binder Characterization

2.3.1 Summary of Findings

The majority of the studies that evaluated the impact of recycled plastics on asphalt binder performance reported its findings in terms of penetration, softening point, viscosity, ductility, or performance grade. For a limited number of studies, multiple stress creep recovery (MSCR) and dynamic shear rheometer (DSR) frequency sweep tests were conducted for binder performance characterization. The overall consistent finding was that the use of recycled plastics for asphalt modification reduced the penetration, ductility, and creep compliance (J_{nr}), and increased the softening point, viscosity, high-temperature performance grade, and elasticity (based on DSR-MSCR phase angle) of asphalt binder. Therefore, asphalt binders modified with recycled plastics should have better rutting resistance than their equivalent unmodified counterparts. Very few studies examined the effect of recycled plastics on asphalt binder properties related to fatigue or low-temperature cracking susceptibility. Those few studies generally reported that the addition of recycled plastics improved the fatigue and low-temperature resistance when a third additive [such as transpolyoctenamer (TPOR), SBS, crumb rubber, or waste vegetable oils] was used for the modification.

A limited number of studies performed analytical evaluation of asphalt binders modified with recycled plastics. From these studies, DSC, modulated DSC, thermogravimetric analysis (TGA), and derivative thermogravimetry (DTG) tests were used to characterize thermal properties; while Fourier transform infrared spectroscopy (FTIR) and scanning electron microscope (SEM) tests were used to characterize chemical properties. Regarding the thermal characterization, the overall consistent finding was that blending temperatures in the range of 170 to 200°C would not be detrimental for the incorporation of recycled plastics into asphalt binders. With respect to the chemical characterization, some studies reported that recycled plastics interacted with the asphalt binders by physical process, while others highlighted the development of chemical interactions.

The inherent incompatibility expressed in terms of phase separation between the recycled plastics and asphalt binder was another topic often evaluated in the “wet process” literature. This incompatibility can be attributed to differences in density and solubility parameters 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 for polymer modified asphalt to maintain its integrity and homogeneity during storage, handling, and mixture production. The evaluation of phase separation typically requires storage stability testing (ASTM D7173) of 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 reports that producing a homogenous and storage-stable binder blend is difficult because the plastic modified binder is 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. Stabilizers and compatibilizers identified as potentially effective include ethylene-vinyl acetate (EVA), maleic anhydride grafted LLDPE, nanosilica, organic montmorillonite, polyphosphoric acid (PPA), reactive elastomeric terpolymer (RET), SBS, crumb rubber, TPOR, waste vegetable oils and sulfur. Low-level chlorination and maleation of PE were also found effective in improving its compatibility with asphalt binder, but the chlorination process could also lead to issues with hazardous chloride-based dioxin emissions. Among these potential stabilizers and compatibilizers, the 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 (Yin et al., 2020), which further complicated the chemical characterization of asphalt binders containing recycled plastics and made solvent extraction and recovery infeasible.

2.3.2 Knowledge Gaps

Because of differences in viscosity and density between recycled plastics and asphalt binders, as well as incompatibilities originating from differences in solubility parameters, RPM binders are prone to phase separate and therefore exhibit poor storage stability. Although existing studies have identified steric stabilizers or compatibilizers which can improve storage stability, the resultant RPM binders still tend to exhibit phase separation after long-term storage, and thus have a limited shelf life. Therefore, 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 could be another 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 used 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.

Existing studies generally agree 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. Durability-related cracking has become the primary form of distress governing the service life of asphalt pavements in the United States. Although a few studies evaluated the effect of recycled plastics on fatigue [based on the DSR $|G^*|\sin(\delta)$ parameter] and low-temperature performance grade and relaxation parameters of asphalt binders, more research should focus on damage resistance testing for assessing these materials, since these tests can rank binders based on ultimate failure parameters instead of stiffness and modulus. Examples of new asphalt binder performance test methods include the linear amplitude sweep (LAS) per AASHTO T 391, binder yield energy test (BYET) per AASHTO TP 123 method B, and the asphalt binder cracking device (ABCD) test (Kim, 2007).

Another research need is to evaluate the applicability of laboratory asphalt binder tests used in the U.S. with RPM asphalt binders, since modifications to current test methods may be needed to accommodate the non-homogeneity of some 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 warm mix asphalt additives, anti-strip agents, and recycling agents. If there are incompatibility issues, the resultant RPM asphalt binders and mixtures will not perform as well as anticipated and could cause premature pavement failures. Finally, certain types of recycled plastics may be insoluble in solvents commonly used for extraction and recovery of asphalt binders and those used in chromatography and spectroscopy characterization techniques for polymers and asphalt binders. Therefore, alternative solvents and testing technologies are needed to accommodate the appropriate characterization of asphalt binders containing recycled plastics.

2.4 Laboratory Mixture Characterization

2.4.1 Summary of Findings

Many of the earlier studies that evaluated the effect of recycled plastics on asphalt mixtures were limited to Marshall properties. In general, most of those studies reported an increase in Marshall stability with the addition of plastics. More recent studies have added other mixture characterization tests including wheel tracking tests, indirect tensile strength, dynamic modulus, various fatigue tests, and other tests. Most research studies found that adding recycled plastics improved rutting resistance and mixture stiffness, but conclusions differed with respect to the impact on fatigue resistance, moisture susceptibility, and indirect tensile strength. The different findings may be attributed to the different types of plastics used, the method of introduction (wet or dry), as well as differences in sample preparation, different tests methods and different test temperatures. A number of studies from India using the dry process claimed that the improvement in mixture rutting resistance could primarily be attributed to coating of aggregates with plastics which increased internal friction within the aggregate structure. These studies also suggested that plastic-coated aggregates had better toughness, abrasion resistance, bond strength, and reduced asphalt absorption.

2.4.2 Knowledge Gaps

The impact of recycled plastics on cracking resistance of asphalt mixtures is not clear. Relatively few studies have evaluated cracking resistance using test methods that are popular in the United States. Given that the interpretation of fatigue test results can be influenced by mixture stiffness and strain levels that are dependent on pavement structure, load magnitudes, and temperature it is not appropriate to make generalized conclusions about the impact of recycled plastics on fatigue cracking based on different studies. Very few studies evaluated low temperature cracking properties. There is also little published information on the effect of aging on mixtures containing recycled plastics. Since most studies found that adding recycled plastics increased the stiffness of asphalt mixtures, a potential value-added application of RPM asphalt mixtures could be as high-modulus layer in a perpetual pavement design. Further investigation of this idea through laboratory testing and pavement design analysis may be warranted to determine if high modulus RPM mixtures could be used to reduce pavement design thickness or help design against bottom-up fatigue cracking.

If volumetric properties are used as part of mix design or quality assurance (QA) testing for RPM asphalt mixtures, particularly those using recycled plastics as aggregate replacement, further examination is also needed to determine the influence of the large differences between specific gravities of the plastic material and natural aggregates and those effects on appropriate criteria for air voids, voids in mineral aggregate, and voids filled with asphalt. Finally, research is needed to evaluate the impact of recycled plastics on the texture characteristics of asphalt mixtures, which will affect the skid resistance, tire-pavement noise and rolling resistance of asphalt pavements.

2.5 Plant Operations

2.5.1 Summary of Findings

Many of the existing studies that documented asphalt plant operations were related to the production of Novophalt®. To overcome the phase separation of Novophalt® binders 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. Since the Novophalt® binders could be directly pumped into the plant for mixing with aggregates without the need for transportation and storage, phase separation was not critical for this approach. However, plant-blending would be challenging on a larger scale because portable blending units with high-shear mixers are expensive and the difficulties with scheduling a limited number of units to serve numerous projects. Furthermore, certification of plant blended RPM asphalt binders for acceptance would be challenging given the susceptibility of these binders to phase separate and the risk associated with the time to get the binder to a lab and tested. Other than the Novophalt® projects, no other studies involving field projects were found that used a portable blending unit.

Rather than using a mobile high-shear blending unit at the asphalt plant, some field studies using the wet process for adding recycled plastics have accomplished the blending at a terminal. Terminal blended RPM asphalt binders must have superior stability to prevent phase separation during transportation and storage at the asphalt plant. Since phase separation is the major challenge for adding recycled plastics via the wet process, QA testing of terminal blended RPM asphalt binders should include the storage stability test, and the QA samples should be taken periodically from the asphalt tank and tested. A benefit of the terminal blending approach is that no major plant modifications are needed to produce RPM asphalt mixtures other than the installment of a mechanically 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. In one study using a recycled PE modified binder, the authors recommended increasing mixing and compaction temperature by 5 to 10°C. The authors also recommended minimizing the time between binder production and mixture production, which could be solved by using a mobile modified binder manufacturing unit.

For the dry process, the two points of introduction identified in the literature were the cold feed conveyor and RAP conveyor (or RAP inlet). However, the former is not recommended from a safety standpoint. The temperature of gases inside the drum can be as high as 760°C (1400°F), 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 fires or even explosions within the mixing drum. Therefore, recycled plastics should be added through the RAP conveyor to avoid direct contact with the burner flame during the mix production process.

To satisfying an agency's desire to verify the consistent dosage of recycled plastics added into the asphalt mixture during production, existing feeder systems used for fibers and other dry additives appear to be suitable for pelletized recycled plastics. These systems provide electronic weigh systems with interlocked controls to adjust the feed as the plant production rate is changed. Calibration of the feeder is required to achieve the desired dosage rate of the plastics.

With regard to plant modifications, one study concluded that using the dry process of adding PS would not increase the production costs of asphalt mixtures since the process does not require significant plant modifications. This conclusion was based on a life cycle assessment performed on mixtures with and without PS.

2.5.2 Knowledge Gaps

A question that still needs to be answered is “Can low melting point recycled plastics be added to a mixing drum so that the plastics uniformly coat aggregate particles as part of a dry process mixing approach.” If so, does the mixing time need to be extended and mixing temperature increased to account for the viscosity of recycled plastics? Furthermore, there is a plant operation concern that recycled plastics could be picked up in the gas stream and be carried to the baghouse where they could blind the filter bags, jeopardizing the operational efficiency of the baghouse and increasing the opportunity for a baghouse fire.

A recent Austroads report indicated that the higher viscosity of plastic modified binders is likely to reduce the overall mixture workability and compactability (Remtulla and Halligan, 2021). Although increasing the mix production temperature could overcome this issue, it is not recommended because it will increase emissions and energy consumption associated with plant production as well as increase fumes exposure to the paving crew. Instead, strategies such as using a softer asphalt binder or using WMA additives should be considered but their effectiveness is yet to be evaluated. The same Austroads report also provided recommendations to asphalt contractors with regards to the production of RPM asphalt mixtures, which include how they receive the recycled plastics, verify that the supplied materials are the correct type(s) of recycled plastics, stockpile the recycled plastics in the correct location, manage stockpiles to ensure traceability of product, and avoid product contamination and damage.

2.6 Construction

2.6.1 Summary of Findings

One study discussed the construction of asphalt mixtures modified with recycled plastics and its effects on mixture properties (Serfass et al., 1992). The study claimed that high-modulus asphalt mixtures produced with PE modification were difficult to compact due to increased binder viscosity and mixture stiffness; thus, heavy rollers were required for construction in order to achieve adequate in-place density. Communications with 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. Another report identified several potential challenges associated with the use of recycled plastics for road construction, including health and safety concerns, generation of microplastics, reuse of polymer modified binders, plastic compatibility, and storage stability (Lin et al., 2020). The study indicated that the release of microplastics can be prevented in a plastic road when waste plastics are heated to the correct temperatures and quality control standards are strictly followed.

2.6.2 Knowledge Gaps

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 the asphalt binder when added via the wet process and possibly the aggregate gradation when added via the dry process, they are likely to affect the workability and compactability of RPM asphalt mixtures. Adding higher dosages of recycle plastics could cause a sharp viscosity increase. Research is needed to assess the significance of this impact. In the United States, warm mix asphalt (WMA) additives are now widely used as compaction aids to help achieve proper in-place density during construction. Studies are needed to evaluate the compatibility between recycled plastics and WMA additives and their combined effects on compactability of RPM asphalt mixtures. A key question that needs to be answered is "Can WMA additives be used with recycled plastics while reducing mixture production temperatures to levels desired for future emission targets?" Since some plastics have a melting point within the temperature range used for WMA compaction, the phase change could negatively affect compactability. Field projects are needed to adapt current construction practices to accommodate recycled plastics, provide an indication of operational costs for incorporating RPM, and provide early indications of the impact on a pavement's service life to assess the costs and benefits related to long term pavement sustainability.

2.7 Health and Safety

2.7.1 Summary of Findings

The literature review identified two potential health and safety concerns regarding the use of recycled plastics in asphalt: (1) leaching of toxic components during processing of recycled plastics, and (2) the generation of chlorine-based gases and dioxin 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 (White, 2019). However, literature references do caution against the use of chlorinated polymers such as PVC.

2.7.2 Knowledge Gaps

There are significant health and safety unknowns 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, typically contain chemical additives that were added in the manufacturing process as well as contaminants and deleterious materials. Some of these recycled plastics can release HAPs including polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (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 for using certain types of recycled plastics in asphalt. These plastics are primarily limited to polytetrafluoroethylene 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 2.5), 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 to cause fire and explosions, nor jeopardize the operation efficiency of the filter bags and cause fire in the baghouse.

2.8 Environmental Impact

2.8.1 Summary of Findings

The literature review suggests that recycling of waste plastics in asphalt pavements could provide 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 (CO_2), sulphur dioxide (SO_2), and nitrogen oxide (NO) emissions. However, these claims were not quantified. A life cycle assessment (LCA) showed a reduced environmental impact associated with the use of RPM modified binders and mixtures for pavement applications. For the production of recycled plastic pellets, the potential environmental impact was driven by the pelletization process due to its high consumption of electric energy. However, a key input of an LCA is the impact of an additive on the service life of the pavement, which is an unknown for recycled plastics. In addition, 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. Few studies have investigated these concerns. One study indicated that the release of microplastics could be potentially prevented by heating the waste plastics to appropriate temperatures and by strictly following quality control standards (Lin et al., 2020).

2.8.2 Knowledge Gaps

Asphalt pavement is the most recyclable material in the United States. According to the latest asphalt pavement industry survey by NAPA, more than 94 percent of asphalt pavements reclaimed in 2018 were put back to use in new pavements and the remaining 6 percent was used in other civil engineering applications (Williams et al., 2020). The recyclability 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 upon completion of their service lives. The subject of RPM mixture aging is not well documented by 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 during milling of asphalt pavements after they have reached the end of their service lives. High crystallinity 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). On the other hand, lower density plastics, which appear to have greater potential for use in asphalt pavements, may not be as susceptible to degradation. According to the United States National Oceanic and Atmospheric Administration (NOAA) and Parliament of Australia, microplastics are any type of plastic fragment that is more than 50μm and less than 5 mm in length (Lin et al., 2020). 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. 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. Although it was highlighted in a technical guidance that release of micro-plastics can be prevented in a plastic-modified road when the waste plastics are heated to the correct temperatures and quality control standards are strictly followed (Lin et al., 2020), their effectiveness has yet to be determined.

Leaching of harmful materials and pollutants such as phthalates, Bisphenol A (BPA), and microplastics from asphalt pavements made with RPM asphalt mixtures is another environmental concern. The potential release of microplastics from a pavement containing recycled plastics may be a greater concern for the dry process given the potentially higher content of recycled plastics with this method. Phthalates and BPA are two types of man-made chemicals used in many common 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 objectionable odors, which have a negative impact on the environment and increase the occupational exposure of asphalt workers to HAPs. Therefore, emissions monitoring, and analysis at asphalt plants and paving sites using RPM asphalt mixtures are needed. Finally, LCA studies are useful tools to holistically assess 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. The Federal Highway Administration (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., 2021).

2.9 Field Projects

2.9.1 Summary of Findings

Over 200 field projects using recycled plastics in asphalt pavements were identified in literature references. There were reportedly more projects constructed in France between the mid-1980s and mid-1990s, 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 (Stuart et al., 2000).

India has reported over 15 years of experience recycling waste plastics in asphalt pavements, in total placing more than 2,500 km of roads using asphalt mixtures containing plastic-coated aggregates. Although several studies reported a successful outcome when 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, China, Columbia, Indonesia, Mexico, the Netherlands, New Zealand, South Africa, the United Kingdom, and the United States. Most of these projects are only a few years old, so the long-term durability of these pavements has yet to be determined.

Table 1 provides a list of trial projects constructed with asphalt mixtures containing recycled plastics since 2018 in the United States. The first "dry plastic" trial project was constructed on the campus of the University of California in San Diego using a proprietary recycled plastic product from MacRebur. Since then, trial projects have been constructed following both dry and wet processes for introducing recycled plastics into the asphalt mixture. The dry process typically uses 0.5 to 1.0% of recycled PE by weight of the aggregate or mixture while the wet process would use up to 2% recycled PE by weight of the binder (and a polymer if needed) to modify an asphalt binder to meet a performance grade specified for the trial project. Six trial projects have been constructed, and two upcoming trials are being planned in Missouri and Pennsylvania.

Table 1. List of Recent Field Projects of RPM Asphalt Mixtures in the United States

Location	Project Type	Project Size	Type of Plastics Used	Quantity of Plastics Used	Process	Year Constructed	Notes
UC San Diego, CA	Local Road	Unknown	LDPE/LLDPE	Unknown	Dry	2018	One mix with a MacRebur product
Dow's Facility Freeport, TX	Private Roads	2,600 ft of roads	LLDPE	1,686 lbs of recycled LLDPE	Wet	2019	PG 70-22 modified with LLDPE & ELVALOY™ RET
Dow's Sabine River Works	Private Roads	3,480 yd^2	LLDPE	1,830 lbs of recycled LLDPE	Wet	2020	PG 76-22 modified with LLDPE & ELVALOY™ RET
Multiple Locations, MI	Four county roads and two parking lots	5.5 lane miles and 30,500 yd^2 of parking area	PIR PE & mixed thermoplastic polymers	10,400 lbs of recycled PE	Wet	2019	PG 64-28P with recycled polyethylene (rPE) & ELVALOY™ RET
Cincinnati Technology Center, OH	Parking Lot	2,885 yd^2 of parking area	LDPE/LLDPE	4,290 lbs of rPE (71,000 retail bags)	Dry	2020	One mix using generic rPE at 0.5% by weight of agg.
Howe Street, Racine, WI	Local Road	450 ft long by 17 ft wide	LDPE/LLDPE	990 lbs of recycled PE	Dry	2020	One mix using generic rPE at 0.5% by weight of agg. and one control
NCAT Test Track, AL	Accelerated Testing	Two 200-ft test sections	LDPE/LLDPE	Unknown	Wet and Dry	2021	Wet process: PG 64-22 modified with 1% rPE &1.75% ELVALOY™ RET; Dry process: 0.5% rPE by weight of agg.
Stadium Blvd, Uni. of Missouri	Local street	Two miles of roads	LLDPE	10 tons of recycled PE	Wet and Dry	Upcoming	One mix with 0.9% ELVALOY™ RET & 0.5% rPE by weight of mix and one control with 0.5% rPE
Ridley Creek State Park Roadway, PA	Local road	Two quarter-mile roadway sections	Unknown	Unknown	Unknown	Upcoming	One section with rPE and one control

2.9.2 Knowledge Gaps

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 a critical 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.

2.10 Other Potential Civil Engineering Applications

2.10.1 Summary of Findings

Recycling waste plastics in construction materials has been considered to support sustainable development. Waste plastics are used as fillers and aggregate in concrete, especially in lightweight concrete as waste plastics have lower density than most natural materials (Choi et al. 2005). Waste plastic bags can be shredded for use as fibers in concrete to improve energy absorption capacity and higher resistance to impact for concrete pavement and barrier applications (Parviz et al. 2003; Jain et al. 2021). Waste plastics can also be used as aggregates in base and subbase, and they have been used to make recycled plastic strips for improving the pavement stiffness and bearing capacity (Benson et al. 1994; Jha et al. 2014). Waste plastics are also used in glass-fiber reinforced composites for manufacturing railway sleepers, benches, decks, fencing, sheeting, garden products, footpaths, components for bridges, and pipes (MuniBajracharya et al. 2014).

2.10.2 Knowledge Gaps

In addition to asphalt pavements, research continues to explore the use of recycled plastics in other civil engineering applications. For example, because of its low density, recycled plastics have the potential for use as alternative lightweight backfill materials for embankments and landscape projects. Furthermore, the aggregate replacement approach 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.

2.11 Ongoing Research

This section provides brief discussions for ongoing research studies on use of recycled plastics in asphalt. These studies were identified from recent conferences and webinars in the asphalt research community, as well as information provided by the project’s International Advisory Committee. Because these studies are still in-progress, the discussions provided below are based on interim test results and research findings that have been published thus far. The Research Team will continue to follow these studies and update this literature review chapter to incorporate findings as they become available throughout the course of NCHRP project 09-66.

2.11.1 Alliance to End Plastic Waste (AEPW) Research

AEPW sponsored two research studies at Chiang Mai University (CMU) in Thailand and National University of Singapore (NSU) to explore the use of recycled plastics in roads. The overall objective of the two studies is to determine the potential pollution impact on air and water and recyclability potential when using recycled plastics in roads. AEPW has been sharing the interim test results and research findings from these two studies with an internal advisory committee (members including NCAT, Asphalt Institute, and Dow in the United States) at its quarterly web meetings, but the information is not available to the public at this point.

2.11.2 Department of Energy (DOE) REMADE Institute Study

The REMADE Institute sponsored a research study at the University of Tennessee – Knoxville in 2020 entitled "*Enabling Cross-industry Reuse of Comingled Waste Plastics as Quality Asphalt Modifier for Sustainable Pavement*." This project seeks to develop and demonstrate a universal strategy to co-stabilize comingled waste plastics with waste tire rubber into asphalt binders. No public information is available regarding the specific scope and progress of this study.

2.11.3 Dow/University of Missouri Collaboration on Pavement for a Circular Economy and Smart City Infrastructure

The following information was provided by Dow: "In May 2019, Dow and the University of Missouri entered into a collaboration to study mixture performance (rutting resistance and low temperature cracking resistance) and microparticle generation of modified asphalt containing recycled PE-rich streams added through the dry process, while targeting (1) maximization of recycled content, and (2) determination of correlation, if any, between plastic content and generation of loose particles. Three paved sections with recycled PE content of up to 0.5 wt% of mix, 30% RAP and including a hybrid wet/dry approach were completed in August 2021 in partnership with the Missouri Department of Transportation."

2.11.4 FHWA Exploratory Advanced Research (EAR) Study

FHWA is funding a research study through its EAR program entitled "*Improving the Compatibility of Waste Plastic and Asphalt Binder via Theoretically Justified Identification of Compatible Blends*." The study was awarded to the Louisiana Tech University, with a start date of September 23, 2020, and completion date of September 22, 2023. According to FHWA, this study seeks to 1) give insight into the fundamental mechanism by which common waste polymers such as HDPE, LDPE, and PET mix/de-mix when blended with asphalt binder with various modifications, 2) optimize said blends, and 3) use that knowledge to develop tests to optimize the modification process before mixing untested binders and waste plastics of specified types. Interim results and research findings of this study are not currently available. More information about this study can be found at: https://highways.dot.gov/research/projects/improving-compatibility-waste-plastic-and-asphalt-binder-theoretically-justified.

2.11.5 National Center for Transportation Infrastructure Durability & Life-Extension (TriDurLE) Study

TriDurLE sponsored a research study at the Missouri University of Science and Technology to conduct a preliminary laboratory investigation on the viability of using recycled plastics in asphalt via the wet process. The objectives of the Phase I study are to: 1) investigate the viability of using recycled plastics in asphalt, 2) investigate the effects of different recycled plastics on the performance properties of wet-process RPM asphalt binders and mixtures, and 3) identify potential issues of using recycled plastics in asphalt. Phase I started in May 2020 and has an anticipated completion date of June 2021. Further phases of this study may include comprehensive lab and field performance evaluation, development of relevant specifications, LCCA, and environmental impact assessment. More information about this study can be found at https://tridurle.wsu.edu/use-of-recycled-plastics-in-asphalt-pavements/.

2.11.6 NCAT-MnROAD Additive Group Experiment

NCAT and the Minnesota Road Research Facility (MnROAD) have initiated a comprehensive field experiment (sponsored by FHWA and six state DOTs) to evaluate the impact of asphalt additives on pavement cracking performance. This experiment includes two sub-experiments, with one on the NCAT Test Track with a focus on bottom-up fatigue cracking and the other to be constructed at MnROAD with a focus on reflective and thermal cracking. The NCAT Test Track sub-experiment consists of six test sections, including two plastic sections, two rubber sections, one fiber section, and one control section. Of the two plastic sections, one introduced the recycled plastic by the dry process and the other used a wet process. The dry process RPM mix was designed by modifying the control mix with a "drop-in" approach, where commercial LDPE-rich PCR plastic pellets were added into the mixture at 0.5 percent by weight of the aggregate. During mix design performance testing, the dry process RPM mix had better rutting resistance in the Hamburg Wheel Tracking Test (HWTT) but reduced cracking resistance in the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and the Cyclic Fatigue test compared to the control mix. The wet process RPM mix used an asphalt binder modified with a RET and the same LDPE-rich PCR plastic as the dry process RPM mix. HWTT, IDEAL-CT, and the Cyclic Fatigue test results from mix design testing indicated that the wet process RPM mix had better or equivalent rutting resistance and cracking resistance than the control mix. FlexPAVE™ simulations predicted the wet-process RPM mix would have the best cracking performance, followed by the control mix, and then the dry process RPM mix. All of the NCAT test sections were constructed in September 2021. No issues were encountered during production and construction of the two plastic sections. The performance of these sections will be monitored over a 3-year research cycle with 10 million ESALs. Plant mixes of these sections were sampled during production and will be tested with a range of laboratory tests for performance characterization and modeling. The MnROAD sub-experiment will be constructed in the summer of 2022. It is anticipated that the MnROAD experiment will also include test sections using a wet and dry process for adding recycled plastics to the mixture.

2.11.7 RMIT University Study

Guppy and Giustozzi (2021) delivered a presentation on "*Use of Waste Plastics in Roads – a Multi Criteria Performance and Environmental Assessment*" at the Australian Flexible Pavement Association (AfPA) 2021 International Flexible Pavement Symposium in August 2021. The presentation introduced an ongoing research study at RMIT University on the evaluation of microplastics from asphalt mixtures containing recycled plastics. As shown in Figure 10, the microplastics evaluation method required conducting the abrasion test on RPM mixture specimens at controlled temperature, water pH, and duration conditions, and collecting the water samples after the abrasion test. The water samples were then filtered to extract the solid residues, which was further separated into asphalt binder, aggregate, and microplastics based on solvent extraction, separation, and filtration. Finally, the microplastic residues were fingerprinted for FTIR and microscopy analysis.

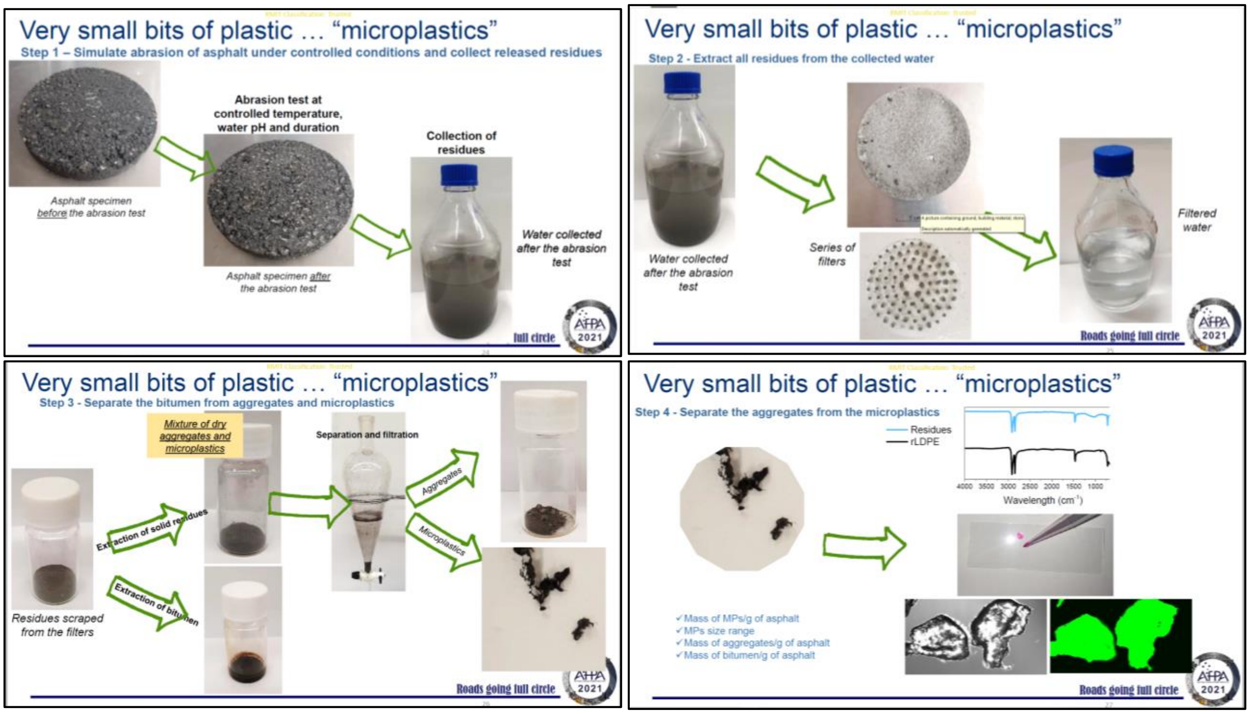


Figure 10. Microplastic Evaluation at RMIT University (Guppy and Giustozzi, 2021)

2.11.8 Texas Department of Transportation (TxDOT) Study

TxDOT sponsored a research study at the University of Texas Arlington on feasibility evaluation of building plastic roads in 2020. Very limited information about the objective and scope of this study can be found at https://www.uta.edu/news/news-releases/2020/04/10/plastic-roads.

2.11.9 University of Massachusetts (UMass) Dartmouth Study

Researchers at UMass Dartmouth presented a research study on use of recycled plastics in asphalt at the 2021 AAPT Annual Meeting in Nashville, TN (Abdalfattah et al., 2021). The objectives of this study were to: 1) evaluate the rheological properties of rPE modified asphalt binders, 2) evaluate the performance of rPE modified asphalt mixtures prepared using wet and dry process, 3) evaluate the effect of rPE type, 4) evaluate the effect of asphalt binder source for a given PG, 4) measure the effect of using rPE on the aging susceptibility of asphalt binders, and 5) determine if rPE modified asphalt mixtures might cause toxicity to ground waters. The key findings of the study were summarized as follows (reprinted from the AAPT presentation):

- Adding rPE to the virgin binders at the critical dosage of 2.5% increased the high temperature PG and reduced the non-recoverable creep compliance which indicates improved rutting resistance.
- rPE asphalt mixtures produced via both dry and wet processes exhibited lower rut depth after 20,000 HWTT passes and higher FN values. Hence, rPE enhanced the rutting resistance of control mixtures.
- rPE at the critical dosage slightly enhanced the fatigue cracking resistances of the virgin binders when measured by the DENT test, while based on |G*|sinδ, they negatively affected fatigue cracking resistance.
- The rPE dosage required for maintaining the low temperature PG was dependent on virgin binder source regardless of rPE source. The DC(T) test results agreed with the low

temperature PG. The EBBR test indicated that rPE could reduce the low temperature cracking resistance during extended field low temperature periods.

- The Black space and ω_c-R value space diagrams indicated that rPE modified binders exhibited higher aging levels than their corresponding virgin binders. Virgin binder source influenced the non-load associated cracking resistance while no effect was observed for rPE source.
- rPE modified mixtures produced using the wet process were more susceptible to intermediate temperature cracking relative to the control mixtures. Additionally, the overall trends of FI and the IDEAL-CT test were consistent and agreed with binder rheological diagrams analyses.
- Mixtures prepared using the dry process showed an inconsistency between the IDEAL-CT and FI measures. This highlights the importance of validating the testing method being implemented by a DOT when evaluating the performance of asphalt mixtures.
- The binder source was a factor in determining the critical dosage.
- The ANOVA analysis showed that the virgin binder source had a significant effect on the CT Index and FI of rPE mixtures designed using the wet and dry processes.
- The mixing process was a factor in determining the critical rPE dosage.
- Based on the embryotoxicity test, rPE could be used in asphalt mixtures without environmental risks.

2.11.10 Virginia Transportation Research Council (VTRC) Study

VTRC has an ongoing research study to document and assess RPM field trials in Virginia. The study seeks to evaluate the constructability, laboratory performance, and short-term field performance of RPM mixtures versus typical Virginia DOT mixtures, as well as detect and quantify the presence of microplastics in material generated from the RPM pavement. Two test sections were constructed in October 2021. One of them used MacRebur's MR6 additive and the other used Kao's PET-based additive NEWTLAC 5500. Both additives were added into the mixtures via the dry process during production. VTRC expects to construct several more test sections using different recycled plastic technologies in 2022. More information about this study can be found at http://vtrc.virginiadot.org/ProjDetails.aspx?id=739.

3. PHASE II WORK PLAN

This chapter presents the proposed Phase II work plan with the objectives of evaluating the impact of PCR plastics on the performance properties, surface characteristics, mix production, process control, and constructability of asphalt mixtures. The performance properties of interest include workability, rutting resistance, fatigue resistance, cracking resistance, moisture susceptibility, and aging resistance. The proposed work plan consists of five laboratory experiments with well-defined research objectives and outcomes described as follows.

- Experiment 1 focuses on selecting various types of PCR plastics by characterizing their key physicochemical properties that are considered important for use in asphalt mixtures via the dry process.
- Experiment 2 seeks to determine the performance properties and surface characteristics of plant-produced RPM asphalt mixtures from two field projects as well as characterize the rheological and chemical properties of extracted RPM asphalt binders.
- Experiment 3 focuses on engaging asphalt contractors with experience in the production of dry-process RPM asphalt mixtures to gather information and develop guidelines for plant setup, production QC, and construction practice.
- Experiment 4 aims at developing a laboratory procedure for adding PCR plastics to simulate the production of RPM mixtures at asphalt plants.
- Experiment 5 primarily focuses on evaluating the performance properties of laboratory-produced RPM asphalt binders and mixtures prepared with various sources and types of PCR plastics, as well as exploring practical mix design modifications to improve the cracking resistance of RPM asphalt mixtures using a BMD approach.

3.1 Selection and Characterization of PCR Plastics (Experiment 1)

Plastics are usually classified by their polymer chemical structure (e.g., acrylics, polyesters, polyurethanes, and silicones) or synthesis process (e.g., polycondensation, polyaddition, and crosslinking). Other classifications are based on the plastic manufacturing or engineering features, such as thermo-plasticity, thermosetting, biodegradability, and elastomericity. However, when using PCR plastics in asphalt, it is necessary to characterize their chemical and physical properties to identify the stream composition, as this will likely impact the performance of RPM asphalt binders and mixtures. For this project, PCR plastics will be classified by their physical properties (e.g., molecular weight, density, degree of polymerization, and crystallinity), chemical properties (e.g., macromolecular structure, chemical resistance to solvents and oxidation), and thermal properties (e.g., melting point and glass transition temperature) as they are considered important for asphalt applications (Willis et al., 2020; Yin et al., 2020).

This project will focus on PCR plastic streams made of semi-crystalline plastics of which the molecular structure is partially crystalline and partially amorphous. PE and PP are among the most common PCR plastics of this category and are specified in the RFP. However, other PCR plastics include PVC, polyamides (nylons), PET, polyurethanes (PU), or a mix of thereof. Table 2 provides a list of candidate PCR plastics for investigation in this research, which are grouped into three categories: single stream plastics, mixed stream plastics (highest priority), and possibly commercial products made of PCR plastics. In this task, the Research Team will work with plastic recycling facilities, through support from PLASTICS, the Association of Plastic Recyclers (APR), and their member companies, to collect up 12 PCR plastic samples with various sources, recycling process, and physicochemical properties. The types of PCR plastics proposed for evaluation will focus on LLDPE, LDPE, HDPE, and certain types of PP, unless otherwise recommended by the

NCHRP panel. These plastic types are selected for two reasons: (1) when combined, they account for the largest proportion of the MSW plastics generated; and (2) they have relatively low melting temperatures and are, therefore, considered most suitable for use in asphalt mixtures.

Table 2. A List of Candidate PCR Plastics for Research Evaluation

PCR Plastic Category	Plastic Type and Product Examples
Single Stream Plastics	LLDPE LDPE HDPE PP
Mixed Stream Plastics	LLDPE/LDPE blend LDPE/HDPE blend HDPE/PP blend
Commercial Plastic Products	GreenMantra's CERANOVUS® PE and PP wax additives MacRebur's MR6 and MR8: PP/PI blend with proprietary polymer additives NecoTECH's NecoPlastics: HDPE/PP/calcium carbonate blend NVIAMG's NewROAD™: HDPE-based polymer blend

Table 3 presents the proposed tests to characterize the physical, chemical, and thermal properties of PCR plastics that are considered important for asphalt applications. These tests are well-known in the field of plastics and are selected following recommendations from NAPA publication IS-142 (Willis et al., 2020) and relevant literature review findings. Based on the test results, the Research Team will work with the NCHRP panel to select five PCR plastic samples and use them to produce RPM asphalt mixtures for comprehensive mixture performance testing as well as rheological and chemical characterization of extracted RPM asphalt binders as discussed later in this report.

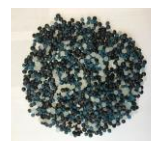
Table 3. Proposed Physical, Chemical, and Thermal Property Characterization of PCR Plastics

Property	Test Method	Importance for Plastics	Impact on RPM Mixtures				
			Interaction with Asphalt Binder	Mix Volumetrics	Mix Workability	Mix Performance Properties	Mix Surface Characteristics
Total Volatiles by Full Evaporation Method	Gas Chromatography (GC)	Measures residual volatile content including limonene					
Melt Flow Index (MFI)	Extrusion (ASTM D1238 Method A)	Indication of resistance to flow (viscosity); key processing parameter	X		X	X	
Melting Point Temperature	DSC (ASTM D3418)	Temperatures at which intermolecular forces disappear and polymer's chain movement occurs allowing viscous flow	X		X	X	
Glass Transition Temperature (T_g)		Temperature at which polymer's glassy state makes a transition to rubbery state due to molecular motion	X		X	X	
Density	Pycnometer (ASTM D792, DSC)	Related to polymer identity and molecular architecture		X			
Particle Size	Sieve analysis	Related to plastic's form and compounding process	X	X		X	X
Ash Content	TGA (ASTM E-1131)	Amount of inorganic residue at 550C	X		X	X	
Functional Groups	FTIR (KBr disc)	Indication of polymer's chemical functions	X		X	X	
Molecular Weight Distribution	Gel Permeation Chromatography (GPC)	Effect on physical properties of asphalt binders, such as viscosity, and temperature susceptibility	X		X	X	

3.2 Performance Characterization of Plant-produced RPM Asphalt Binders and Mixtures (Experiment 2)

The objective of this experiment is to characterize the performance properties and surface characteristics of plant-produced RPM *versus* non-RPM (i.e., control) asphalt binders and mixtures from two field projects in Ohio and Wisconsin. Both projects were constructed in late 2020 through PLASTICS's *Asphalt Early Adopter Cohort* efforts with consulting support provided by NCAT. Each field project included an RPM mixture and a non-RPM control mixture. For each project, the two mixtures were identical except that PCR plastics were added into the RPM mixture via the dry process. Both projects used 9.5 mm nominal maximum aggregate size, dense-graded mixtures containing a PG 58-28 virgin binder. The mixtures from the Ohio project contained 10 percent RAP, while those from the Wisconsin project contained 27 percent RAP. Table 4 summarizes the key properties of the PCR plastic samples used in the two projects.

Table 4. Key Properties of PCR Plastic Samples Used in the Field Projects

Field Project	Polymer Make-up	Melting Temperature (°C)	MFI (190°C, g/10 min)	Specific Gravity	Ash Content (%)	Average Particle Size (mm)	Picture
OH	LLDPE/ LDPE blend	124°C	0.62	0.948	1.76	3.81	
WI	LDPE/ HDPE blend	120°C	N/A	0.939	7.10	2.43	

Because the scope of this NCHRP project is focused on the dry process, the proposed testing plan primarily focuses on performance testing of RPM and control asphalt mixtures, as shown in Table 5. These mixture performance tests are selected based on the preferred mixture performance tests among state highway agencies, supplemented with additional research test methods for asphalt mixture characterization at the NCAT Test Track, MnROAD, and FHWA's Pavement Testing Facility (Golalipour, 2020; Vrtis, 2020; West, 2020; Yin and West, 2021).

The proposed mixture performance tests in Table 5 are intended to evaluate the impacts of PCR plastics on the workability, rutting resistance, moisture susceptibility, cracking resistance, fatigue damage, and aging resistance of asphalt mixtures. The workability, rutting, and moisture damage tests will be conducted on reheated plant-mixed, lab-compacted (PMLC) specimens. To consider the impact of asphalt aging, the mixture fatigue and cracking tests will be conducted on PMLC specimens that have been subjected to additional long-term aging after reheating. Two candidate mixture long-term aging protocols for use in this research are loose mix aging for 5 days at 95°C and 8 hours at 135°C per recommendations from NCHRP project 9-54 and the MnROAD/NCAT Cracking Group experiments, respectively, which are expected to simulate approximately 4 to 6 years of field aging in the United States (Chen et al., 2018; Chen, 2020; Kim et al., 2020). The small-specimen Dynamic Modulus (E*) test will be conducted on both reheated and long-term aged PMLC specimens to assess the aging resistance of RPM *versus* control asphalt mixtures. For quantitative comparison purposes, the E* results will be analyzed using aging indices of the E* value at 20°C and 10 Hz as well as the mixture Glover-Rowe parameter (G-R_m) investigated under NCHRP project 9-58 (Epps Martin et al., 2020). Furthermore, the AMPT E* and Cyclic Fatigue test results will be input into the FlexPAVE™ program to determine the impact of adding PCR plastics on predicted cracking performance of asphalt pavements under various pavement structure, climate, and traffic conditions.

Table 5. Proposed Performance Testing of Plant-Produced RPM and Control Mixtures

Mixture Property	Performance Test (AASHTO/ASTM Standard)	Aging Condition	Test Parameter
Workability	Dongre Workability Test (DWT) (Dongre et al., 2020)	Short-term Aging	DWT Workability Value at 225, 250, and 275°F
Rutting Resistance	HWTT (T 324), Indirect Tensile Asphalt Rutting Test (IDEAL-RT) (Zhou et al., 2020)		Total Rut Depth (TRD), Rutting Tolerance Index (RT_{index})
Moisture Susceptibility	HWTT (T 324), Tensile Strength Ratio (TSR) (T 283)		Stripping Inflection Point (SIP), Tensile Strength Ratio (TSR)
Intermediate Temperature Cracking Resistance	IDEAL-CT (D8225)	Long-term Aging	Cracking Tolerance Index (CT_{index})
Low Temperature Cracking Resistance	Disc-shaped Compact Tension (D7317)		Fracture Energy (G_f)
Fatigue Damage Characteristics	Cyclic Fatigue (TP 133)		C *versus* S Curve, Fatigue Index Parameter (S_{app}), FlexPAVE™ Cracking Performance Prediction
Aging Resistance	Dynamic Modulus (TP 132)	Short- and Long-term Aging	E* Aging Index, G-R_m Aging Index

In addition to the mixture performance testing described above, slab specimens will be prepared and subjected to surface weathering in the NCAT Accelerated Weathering System (NAWS) followed by up to 150,000 cycles of surface polishing in the NCAT Three Wheel Polishing Device (TWPD), as shown in Figure 11 and Figure 12. The surface weathering in NAWS simulates the long-term exposure of asphalt pavements to moisture, heat, and ultraviolet light simultaneously. Surface friction and texture measurements will be made on the slab specimens before, during, and after TWPD polishing using the Dynamic Friction Tester (DFT) and Circular Texture Meter (CTM). To assess the impact of PCR plastics on the surface and texture characteristics of asphalt mixtures, the average dynamic friction at 40 km/h (DFT40) and mean texture depth (MTD) results of RPM mixtures will be compared against those of the control mixtures as a function of polishing cycles in TWPD.

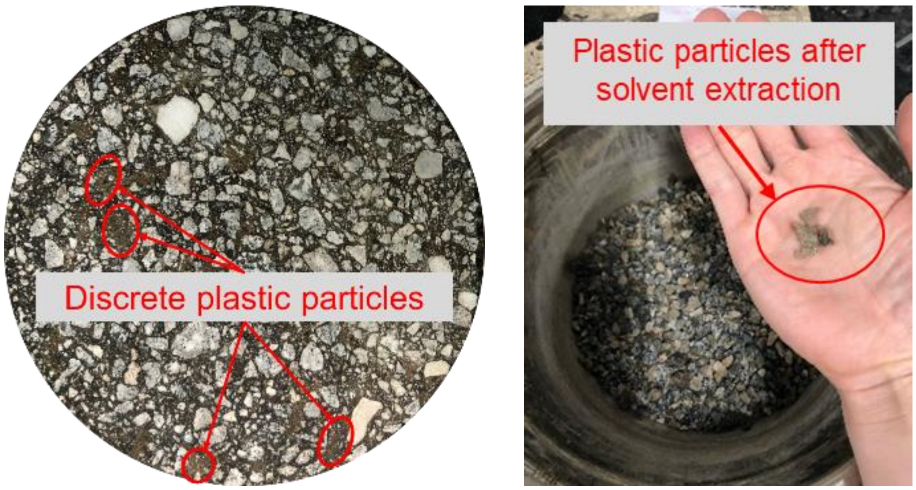
Figure 11. NCAT Accelerated Weathering System (NAWS)

Figure 12. NCAT Three Wheel Polishing Device (TWPD)

In preparation for this project, the Research Team conducted a proof-of-concept experiment to assess the mingling of PCR plastics with asphalt binders using the dry process and determine their impact on the rheological and chemical properties of asphalt binders extracted and recovered from RPM asphalt mixtures. It was hypothesized that the laboratory mixing process could result in some of the PCR plastics blending into the asphalt binder, although the degree of interaction between the PCR plastics and asphalt binder was unknown. If an interaction of the plastic and binder occurred, it would change the rheological properties of asphalt binder that could be evaluated after solvent extraction and recovery. Two laboratory-produced asphalt mixtures containing a PG 58-28 virgin binder and 20% RAP, with and without PCR plastics, were evaluated. DSR and Bending Beam Rheometer (BBR) results of the extracted binders supported the hypothesis that interaction between PCR plastics and asphalt binder occurred during the production of dry-process RPM asphalt mixtures. As shown in Table 6, the extracted RPM asphalt binder had higher continuous performance grades and a more negative delta T_c (ΔT_c) value than the control binder, which indicated that the presence of PCR plastics resulted in an overall stiffening effect and loss of relaxation properties on the asphalt binder. PCR plastic particles were also visually evident in the aggregate remaining after solvent extraction, as shown in Figure 13(b). Ignition furnace testing of the extracted aggregate and plastic residue indicated that only about 10 percent of PCR plastics added into the RPM mixture were dissolved into the asphalt binder, while the rest remained as discrete plastic particles in the mixture phase [Figure 13(a)].

Table 6. Continuous PG and ΔT_c Results of Extracted RPM *versus* Control Asphalt Binders in the NCAT Proof-of-Concept Experiment

Mix ID	T_c High (°C)	T_c Intermediate (°C)	T_c Low, Stiffness (°C)	T_c Low, m-value (°C)	Delta T_c (°C)	PG Grade
Control	81.8	23.1	-28.5	-24.2	-4.3	76-22
RPM	91.5	27.1	-26.4	-18.1	-8.4	88-16



(a) (b)

Figure 13. PCR Plastic Particles; (a) Before, and (b) After Solvent Extraction (per ASTM D2172 method A) using Trichloroethylene (TCE) and Recovery (per ASTM D5404)

Furthermore, the Research Team evaluated the solubility of the PCR plastic sample in trichlorobenzene (TCB) as a function of temperature (20 to 170°C) and the concentration of PCR plastic (0 to 10 w/v%). As shown in Table 7, the plastic sample became soluble at elevated temperatures above 150°C while the solubility varied as a function of PCR plastic concentration. The state of the plastic sample in TCB changed from insoluble to swollen, and then to soluble with intermediate stages (layers and cloudiness) as temperature increased. These results confirm the potential and limited compatibility of PCR plastics in asphalt binders.

Table 7. Solubility of PCR Plastic Sample in TCB

<table>
<tr><th rowspan="2">Plastic Concentration (w/v%)</th><th colspan="7">Temperature (°C)</th></tr>
<tr><th>20</th><th>70</th><th>115</th><th>130</th><th>150</th><th>160</th><th>170</th></tr>
<tr><td>1%</td><td colspan="2">Insoluble</td><td colspan="2">Polymer swelling</td><td>Cloudy solution</td><td colspan="2">Soluble</td></tr>
<tr><td>2.5%</td><td colspan="2">Insoluble</td><td colspan="2">Polymer swelling</td><td>Cloudy solution</td><td colspan="2">Soluble</td></tr>
<tr><td>5%</td><td colspan="2">Insoluble</td><td colspan="2">Polymer swelling with layers</td><td>Cloudy solution with layers</td><td>Very cloudy solution</td><td>Soluble</td></tr>
<tr><td>10%</td><td colspan="2">Insoluble</td><td colspan="2">Polymer swelling with layers</td><td>Cloudy solution with layers</td><td>Cloudy solution with insoluble solute</td><td>Very cloudy and viscous solution</td></tr>
</table>

Given the results of the aforementioned experiment, the Research Team proposes to include rheological and chemical characterization of extracted RPM and control asphalt binders in this project. As shown in Table 8, a variety of rheological tests will be used to evaluate the viscosity-temperature characteristics, performance grade, and resistance to intermediate- and low-temperature cracking of asphalt binders extracted and recovered from plant-produced RPM *versus* control mixtures. The MSCR test will be conducted to evaluate the impact of PCR plastics on the rutting resistance, elastic response, and stress and temperature dependence of asphalt binders. The extracted and recovered asphalt binders will be subjected to long-term oxidative aging in the Pressure Aging Vessel (PAV) prior to fatigue and cracking evaluation. The LAS test will be conducted to evaluate the fatigue damage resistance of extracted RPM *versus* control asphalt binders. The durability and resistance to thermally induced surface damage of binders will be evaluated by means of ΔT_c and the Glover-Rowe parameter (G-R). Moreover, the thermal contraction of asphalt binders will be investigated using the ABCD test by determining the cracking temperature (T_{cr}) and the ΔT_f parameter [$\Delta T_f = T_c(S) - T_{cr}$] developed under NCHRP project 9-60 (Planche et al., 2020).

Table 8. Proposed Rheological Testing of Extracted RPM *versus* Control Asphalt Binders

Property	Test	AASHTO Standard	Testing		Research Parameter
			Conditions	Aging Level	
Viscosity	Rotational Viscosity	T 316	@ 135, 150, and 165°C	As extracted	Viscosity
Performance Grading	DSR	M 320	@ High PG Temp.	As extracted	$\lvert G^*\rvert/\sin(\delta)$
			@ Intermediate PG Temp.	As extracted + PAV	$\lvert G^*\rvert\sin(\delta)$
		M 332	@ High PG Temp.	As extracted	$J_{nr3.2}$, $\%R_{3.2}$, $\%J_{nr}$ Diff.
Intermediate Temperature Cracking Resistance	LAS	T 391	Frequency & Amplitude Sweep @ Intermediate PG Temp.	As extracted + PAV	Cycles to Failure (N_f), A_{35}, B
	DSR Master Curve	T 315	Frequency Sweep (0.1 to 30 Hz, 10-70°C)	As extracted, As extracted + PAV	G-R Parameter, Black Space Diagram
Low Temperature Cracking Resistance	DSR 4-mm geometry	FHWA-HRT-15-053 (FHWA, 2017)	@ Low PG Temp.	As extracted + PAV	Stiffness, m-value & ΔT_c
	ABCD	TP 92	@ Low PG Temp.	As extracted + PAV	T_{cr}, Fracture Strength, ΔT_f

The proposed chemical characterization tests in Table 9 are expected to provide a fundamental understanding of the molecular structure, thermal responses, surface morphology, and chemical composition of asphalt binders after interaction with PCR plastics when they are added using the dry process. These tests will also provide insights on the fraction of PCR plastics compatible with asphalt binder. Furthermore, this characterization will be useful to indicate the level of interaction between the two materials by capturing the resulting changes in the binder properties. Finally, ignition furnace testing will be conducted on the extracted aggregate and plastic residue to estimate the percentage of PCR plastics that is dissolved in the asphalt binder *versus* the portion of the plastic that remains in the solid state. These rheological and chemical analyses will be conducted on asphalt binders extracted and recovered from the plant-produced RPM and control mixtures from the Ohio and Wisconsin projects. It should be noted that the solubility of recycled plastics in the solvents used for binder extraction as well as analytical evaluation will play an important role in the evaluation of RPM asphalt binders. This is in line with findings from previous studies (Yin et al., 2020) as described in Section 2.3.1.

Table 9. Proposed Chemical Testing of Extracted RPM *versus* Control RPM Asphalt Binders

Property	Test	Research Parameter
Molecular Weight	Saturates, Aromatics, Resins-Asphaltene Determinator (SAR-AD™) Size Exclusion Chromatography (SEC)**	Changes in molecular weight of binders to indicate the presence of PCR plastics
Molecular Structure	FTIR-Attenuated Total Reflection (ATR)**	Functional Groups to indicate asphalt oxidation level which influences PCR plastics (in)compatibility, as well as the presence of PCR plastics, additives, or pollution
Freezing, Melting, and Solubility	Waxphaltene Determinator**	Detection of waxy, polar, and pericondensed aromatic components to measure the content of PCR plastics and asphalt waxes
Thermal Properties	DSC*	Phase transition, crystallization, and glass transition parameters to indicate presence of PCR plastics, and their interaction with asphalt through changes in thermal events.
Surface Morphology	Optical Microscopy*	Multiphase system, plastic crystals, swelling, and interactions of asphalt wax bee structures with plastic crystals
Chemical Composition	SAR-AD™ Fractionation**	Saturates, Aromatics, Resins, and Asphaltenes fractions and subfractions to characterize asphalt matrix composition and possible plastic mingling (or no mingling)

* Test results subjected to the solubility of waste plastics in the solvent used for binder extraction.
** Test results subjected to the solubility of waste plastics in the solvents used for binder extraction and analytical evaluation.

3.3 Development of Guidelines for Constructability, Production Control, and Process Control of Plant-produced RPM Asphalt Mixtures (Experiment 3)

As noted in NAPA publication IS-142 (Willis et al., 2020), one of the knowledge gaps is a lack of acceptance limits for recycled plastics. This report suggests that, at a minimum, specifications should be established for consistency, cleanliness, and particle size. A measure of consistency for recycled plastics could be MFI (or melt flow rate) as defined by ASTM D1238-20, which is a relatively simple, quick, and inexpensive test (equipment cost under $3,000) suitable for QC of polyolefins. A common sieve analysis may be suitable for determining the particle size distribution for recycled plastics supplied in pellet form, although the extrusion process for making pellets generally provides a very uniform size range. However, PCR plastics supplied in other forms such as flakes, shredded film, or powder (Figure 14) are likely to require a modified sieve analysis procedure such as using rubber balls on the sieves as with recycled tire rubber or vacuum assisted sieving as with fibers. For cleanliness, the ash content of plastics as defined by ASTM D5630-13 may be suitable. For each of these QC methods, research is needed to establish reasonable limits considering the ability of PCR plastic suppliers to produce a low-cost product made from post-consumer materials that also meets the needs of the asphalt industry to make quality mixtures with consistent properties.

Figure 14. Samples of PCR Plastics Provided in Different Forms; (a) Pellets, (b) Shredded Films, (c) Flakes, (d) Granules

For continuous asphalt plants, the dry process is likely to utilize well-known metering/feeding systems for adding cellulose fibers for Stone Matrix Asphalt and Open-Graded Friction Course mixtures and other dry additives. This approach was used in the Ohio project where the contractor used a pneumatic feeder from Hi-Tech Asphalt Solutions Inc. to meter PCR plastics at the desired rate into an Astec Double Barrel® XTM plant at the RAP collar in the outer drum, as shown in Figure 15. For batch plants, pre-weighed meltable bags may be added to the pugmill for small tonnage projects that would not justify the addition of an automated feeding system.

Figure 15. Pneumatic Feeder and Entry Point at the RAP Inlet for Adding PCR Plastics in the Ohio Project

In this experiment, the Research Team will develop a questionnaire to send to asphalt mixture producers that have used the dry-process addition of recycled plastics in asphalt plants, including the two field projects in Ohio and Wisconsin discussed in Experiment 2. Since there are currently very few producers with this experience in the United States, the Research Team will use its IAC to collect information from experienced asphalt mixture producers in other parts of the world. The questionnaire will gather information on suppliers of PCR plastics, forms of supplied PRC plastics (e.g. pellets, flakes, granules), container types, QC documentation [e.g., size distribution, contaminants, moisture content, composition (plastic types), physicochemical properties of the plastics], type of asphalt plant (i.e., continuous or batch), method used to feed PCR plastics into the plant, point of entry to the plant's mixing process, temperature of aggregate at the point of entry, feeder calibration process and accuracy, interlock of feeder control to the plant controls, issues with feeder clogging, impact on mix production rate, and issues with non-uniform dispersion of PCR plastics in the mix. The questionnaire will also gather information on QC methods (e.g., methods for determining asphalt content and plastics content) and consistency of the mix properties (e.g., P_b, G_{mm}, G_{mb}, IDT strength) as well as mix handling and constructability information such as noticeable odors, mix stiffness, build-up on paver parts and hand tools, and differences in compactive effort and in-place density results relative to a control mixture without PCR plastics.

The Research Team has had preliminary discussions with major United States asphalt plant manufacturers regarding mixing time and temperature profiles for various points of entry and mix conditions (e.g., RAP content, RAP moisture content, desired mix temperature). This information will guide the team in developing a laboratory procedure for adding PCR plastics to simulate the production of dry-process RPM mixtures at asphalt plants in Experiment 4. Based on information collected from this experiment, the Research Team will develop preliminary recommendations for: 1) QC testing of PCR plastics for use in asphalt, 2) approaches for feeding PCR plastics in asphalt plants, including calibration, points of entry, and mixing times and temperatures, and 3) process control procedures for evaluating plant-produced asphalt mixtures containing PCR plastics.

3.4 Development of a Laboratory Procedure for Adding PCR Plastics to Simulate the Production of Dry-process RPM Asphalt Mixtures at Asphalt Plants (Experiment 4)

The objective of this experiment is to evaluate several laboratory procedures for dry-process addition of PCR plastics and to recommend the procedure that best simulates the production of RPM mixtures at asphalt plants. Based on the prior experience with the dry process of adding PCR plastics, the Research Team proposes four candidate laboratory mixing procedures:

1) Mixing PCR plastics with preheated aggregates at 170 to 180°C, followed by adding preheated RAP at 135°C and then adding the virgin asphalt binder.
2) Mixing PCR plastics with super-heated aggregates at 210 to 230°C, followed by adding ambient temperature RAP and then adding the virgin asphalt binder.
3) Preheating PCR plastics with RAP for 2 hours at 135°C, and then mixing with preheated aggregates at 170 to 180°C and the virgin asphalt binder.
4) Preheating PCR plastics with aggregate overnight at 170 to 180°C, and then mixing with preheated RAP at 135°C and the virgin asphalt binder.

Research studies in India have indicated that the first mixing procedure is most representative of plant production, where recycled plastics are added in direct contact with heated aggregate to create a thin film of plastic coating over the surface of aggregate particles (Awward and Shbeeb, 2007; CPCB, 2008). However, the Research Team investigated this procedure and found the plastic coating hypothesis was not feasible due to lack of high temperature and shear action required to melt ambient temperature PCR plastics during laboratory mixing. Figure 16 presents pictures of LDPE-rich PCR plastic samples before and after dry mixing with preheated aggregates at various laboratory mixing conditions. Thus, three alternative mixing procedures are proposed for evaluation in Experiment 4 to select one that best simulates the plant production. The main difference among these procedures is the temperature history of PCR plastics prior to mixing. Relative to their melting point ranges, this difference may affect their behavior during mixing, the degree of aggregating coating with PCR plastics, and the degree of interaction between PCR plastics and asphalt binder, possibly yielding asphalt mixtures with different performance properties.

(a) (b) (c) (d)

Figure 16. LDPE-rich PCR Plastic Samples; (a) Before Mixing with Aggregates, (b) After Mixing for 30 Seconds at 171°C, (c) After Mixing for 2 Minutes at 188°C, and (d) After Mixing for 4 Minutes at 188°C

Raw materials sampled from the two field projects in Ohio and Wisconsin will be used in this experiment. For each plant-produced RPM asphalt mixture, four sets of LMLC specimens will be prepared following the same material proportions utilized during plant production but with different mixing procedures discussed above. During mixing, the evaluation of fume emissions attributed the addition of PCR plastics will be conducted using two approaches: 1) controlled laboratory experiments with small volumes of material to identify potential compounds from using PCR material, and 2) fume emissions testing from larger scale preparations.

The large-scale samples will be collected during the four different laboratory mixing procedures for dry-process addition of PCR plastics. For the controlled laboratory study, small volumes of material will be performed by Dow Inc. through direct headspace-gas chromatography (headspace-GC). In headspace-GC, a sample is volatilized and carried by an inert gas through a coated glass capillary column, where a stationary phase is bonded to the interior of the column. The time it takes a specific compound to pass through the column to a detector is called retention time and can be used for identification of compounds when compared to a reference. The proposed headspace-GC method has been successfully used for analysis of VOCs compounds released during the preparation of asphalt mixtures in a laboratory environment (Stroup-Gardiner and Lange, 2005; Osborn, 2015). The Agilent MassHunter Unknowns Analysis will be used as the pre-processing tool for the headspace GC/MS data and consists of an integrated set of procedures for first extracting pure component spectra and related information from complex chromatograms, then using this information to determine whether the component can be identified as one of the compounds represented in a reference library (Mallard and Reed, 1997). Using a pre-processing tool permits traditional library searching for any selected component. The practical goal is to reduce the effort involved in identifying compounds by GC/MS while maintaining the high level of reliability associated with traditional analysis. Test results will indicate whether adding PCR plastics via the dry process would result in hazardous VOCs during common mixing processes in a mix design laboratory. For the large-scale samples collected during the four different laboratory mixing procedures, the collection of emissions will be conducted by taking air samples through a particulate filter and adsorption tube assembly, which will be analyzed by validated analytical methods for analytes including VOCs and PAHs.

Furthermore, the volumetric and performance properties of lab-produced RPM mixtures will be compared against of those of plant-produced RPM mixtures using statistical analyses such as two sample t-test and analysis of variance. Three mixture performance tests will be conducted in this experiment:

- IDEAL-RT for the evaluation of rutting resistance.
- IDEAL-CT for the evaluation of intermediate-temperature cracking resistance.
- DCT for the evaluation of low-temperature cracking resistance.

The Research Team will incorporate the results of this experiment in the manual for handling and using PCR plastics in an asphalt laboratory setting as a project deliverable.

3.5 Performance Characterization of Laboratory-produced RPM Asphalt Binders and Mixtures (Experiment 5)

The objective of this experiment is twofold: first, to characterize the volumetric and performance properties of laboratory-produced RPM asphalt binders and mixtures containing different sources and types of PCR plastics; and second, to explore mix design modifications to improve the fatigue and cracking resistance of RPM asphalt mixtures using a BMD approach. Two agency-approved volumetric mix designs will be used in this experiment: one from a Northern state and the other from a Southern state. For each mix design, a control mixture and five RPM mixtures will be prepared following the job mix formula. The RPM mixtures will be prepared with different sources and types of PCR plastics selected in Experiment 1. PCR plastics will be added using the laboratory procedure selected in Experiment 4. Each PCR plastic will be tested at one dosage rate.

The proposed testing plan for laboratory-produced control and RPM asphalt binders and mixtures is the same with Experiment 2 (Tables 5, 8, and 9), with two exceptions: (1) mixture volumetric testing and analyses will be conducted in addition to performance testing, and (2) rheological and chemical testing of extracted asphalt binders will only be conducted on selected RPM mixtures due to budget limitations. Test results from this experiment will indicate how changes in the source and type of PCR plastics would affect the performance properties of RPM asphalt and mixtures as well the rheological and chemical properties of extracted asphalt binders.

In preparation for this project, the Research Team conducted a laboratory experiment on the volumetric and performance testing of two asphalt mixtures with and without PCR plastics. The two mixtures used a PG 58-28 virgin binder and 20% RAP. The RPM mixture was prepared by adding LDPE-rich PCR plastics at a dosage of 0.8 percent by weight of aggregate. Table 10 summarizes the experiment results. Adding PCR plastics via the dry process reduced the G_{mm} and N_{design} air voids of the mixture. The RPM mixture showed better rutting and moisture resistance in HWTT but reduced fatigue damage resistance in the AMPT Cyclic Fatigue test than the control mixture. Furthermore, the RPM mixture had a higher $G\text{-}R_m$ value and was likely to be more susceptible to block cracking than the control mixture. Finally, the two mixtures had statistically equivalent CT_{index} values at both short-term and long-term aging conditions, which disagreed with the Cyclic Fatigue test results. This discrepancy will be further investigated in this project.

Test results in Table 10 indicated that the dry process of adding PCR plastics may have a negative impact on the fatigue and cracking resistance of asphalt mixtures, which may be due to increased mixture stiffness and reduced relaxation properties. To overcome this issue, additional performance testing will be conducted on two selected RPM mixtures in this experiment to explore potential mix design modifications to improve their cracking performance using a BMD approach. The proposed modification approaches include using a softer virgin binder, increasing the asphalt binder content, and reducing the RAP content. The selected RPM mixtures with and without the proposed design modifications will be tested in IDEAL-CT, DCT, and AMPT Cyclic Fatigue. For mix design modifications that prove effective, cost analyses will be conducted to compare the materials cost of RPM *versus* non-RPM control mixtures with similar cracking test results.

Table 10. Test Results of Control *versus* RPM Mixtures in the NCAT Experiment

Test Results	Control Mixture	RPM Mixture
G_{mm}	2.493	2.462
N_{design} Air Voids (%)	4.5	3.5
HWTT Rut Depth at 20,000 Passes (mm)	> 12.5	2.5
HWTT Stripping Inflection Point (SIP)	14,000	> 20,000
IDEAL CT_{index} (short-term aged)	38.6	45.9
IDEAL CT_{index} (long-term aged)	15.8	15.9
$G\text{-}R_m$ (MPa)	8,133.1	9,164.3
Cyclic Fatigue S_{app} at 21°C	21.7	9.6

REFERENCES

Abdalfattah I. A., Mogawer W.S., and Stuart K.D., 2021. Recycled Polyethylene (RPE) Modified Asphalt Binders and Mixtures: Performance Characteristics and Environmental Impact. 2021 AAPT Annual Meeting, Nashville, TN.

Aschuri, I. and Woodward, D., 2010. Modification of a 14mm asphalt concrete surfacing using RAP and waste HDPE plastic. International Journal of Pavements, 9(1-2-3), pp.70-78.

Bajracharya, R.M., Manalo, A.C., Karunasena, W., and Lau, K.T., 2014. An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites. Materials & Design (1980-2015), 62, pp.98-112.

Bardesi, A., Brule, B., Corte, J. F., Diani, E., Gerritsen, A., Lefevre, G., and Watkins, S. (1999). Use of modified bituminous binders, special bitumens and bitumens with additives in pavement applications. Technical Committee Flexible Roads (C8) World Road Association (PIARC)

Bassett, D.C., 1981. Principles of polymer morphology. CUP Archive.

Benson, C.H. and Khire, M.V., 1994. Reinforcing sand with strips of reclaimed high-density polyethylene. Journal of Geotechnical Engineering, 120(5), pp.838-855.

Bhawan, P. and Nagar, E.A., 2008. Performance Evaluation of Polymer Coated Bitumen Built Roads.

Bredael, P., 1993. Utilisation de polyéthylène haute densité recyclé pour revêtements routiers. In 5th Eurobitume Congress, Stockholm (Vol. 2, pp. 408-412).

Bremner, T., Rudin, A., and Cook, D.G., 1990. Melt flow index values and molecular weight distributions of commercial thermoplastics. Journal of Applied Polymer Science, 41(7 - 8), pp.1617-1627.

Chen, C., 2020. Validation of Laboratory Cracking Tests for Field Top-down Cracking Performance (Doctoral dissertation, Auburn University).

Chen, C., Yin, F., Turner, P., West, R.C., and Tran, N., 2018. Selecting a laboratory loose mix aging protocol for the NCAT top-down cracking experiment. Transportation Research Record, 2672(28), pp.359-371.

Chin, C. and Damen, P., 2019. Viability of using recycled plastics in asphalt and sprayed sealing applications.

Choi, Y.W., Moon, D.J., Chung, J.S., and Cho, S.K., 2005. Effects of waste PET bottles aggregate on the properties of concrete. Cement and concrete research, 35(4), pp.776-781.

Dongre, R., Li, X., and Youtcheff, J., 2020. A Simple Test for Quality Control of RAP Piles. Proceedings of the 7th E&E CONGRESS Eurasphalt & Eurobitume.

DuBois, C., 2020. Wet Processed Plastics in Asphalt. Transportation Research Board, Washington, D.C, Presented on January 13, 2020.

Environmental Protection Agency (EPA)., 2018. How Do I Recycle?: Common Recyclables. [Online] Available at: https://www.epa.gov/recycle/how-do-i-recycle-common-recyclables

Environmental Protection Agency (EPA)., 2020. Advancing Sustainable Materials Management:2018 Fact Sheet.

Environmental Protection Agency (EPA)., 2021. Plastics: Material-Specific Data. [Online] Available at: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data

Federal Highway Administration (FHWA), 2017. Four-mm Dynamic Shear Rheometry.

Gigault, J., Ter Halle, A., Baudrimont, M., Pascal, P.Y., Gauffre, F., Phi, T.L., El Hadri, H., Grassl, B., and Reynaud, S., 2018. Current opinion: what is a nanoplastic?. Environmental pollution, 235, pp.1030-1034.

Golalipour, A., Veginati, V., and Mensching, D.J. (2021) 'Evaluation of Asphalt Mixture Performance Using Cracking and Durability Tests at a Full-Scale Pavement Facility', Transportation Research Record. doi: 10.1177/03611981211021856.

Guppy, R. and Giustozzi, F., 2021. Use of Waste Plastics in Roads – A Multi Criteria Performance and Environmental Assessment. AfPA International Flexible Pavements Symposium.

Harbinson, B. and Azim, R., 1994. The Development and Performance of an Environmentally Responsible Modified Binder. Proceedings of the 9th AAPA International Asphalt Conference.

Harvey, J., Meijer, J., and Kendall, A., 2014. Life Cycle Assessment of Pavements: [Techbrief] (No. FHWA-HIF-15-001). United States. Federal Highway Administration.

Hogue, C., 2019. Guide to PFAS in our environment debuts. Chemical & Engineering News, 97(21), pp.12-12.

Jain, A., Siddique, S., Gupta, T., Jain, S., Sharma, R.K., and Chaudhary, S., 2021. Evaluation of concrete containing waste plastic shredded fibers: Ductility properties. Structural Concrete, 22(1), pp.566-575.

Jha, J.N., Choudhary, A.K., Gill, K.S., and Shukla, S.K., 2014. Behavior of plastic waste fiber-reinforced industrial wastes in pavement applications. International Journal of Geotechnical Engineering, 8(3), pp.277-286.

Khurshid, M.B., Ahmed, S., Irfan, M., and Mehmood, S., 2013, July. Comparative analysis of conventional and waste polyethylene modified bituminous mixes. In The International Conference on Remote Sensing, Environment and Transportation En (RSETE-2013) (pp. 346-349).

Kim, S.S., 2007. Development of an asphalt binder cracking device. IDEA Program, Transportation Research Board.

Kim, Y.R., Castorena, C., Saleh, N.F., Braswell, E., Elwardany, M., and Rad, F.Y., 2020. NCHRP 09-54 Extension Report: Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction. Transportation Research Board, Washington, DC.

Kolek, Z., 2001. Recycled polymers from food packaging in relation to environmental protection. Polish Journal of Environmental Studies, 10(1), pp.73-76.

Lin, D.Y.H., Dong, K.J., Bakshi, H., Yi, R.Y., and Kumar, P., 2020. Use of Recycled Plastic in Local Roads in Regional Areas.

Mallard, W.G. and Reed, J., 1997. Automated Mass Spectral Deconvolution and Identification System AMDIS-USER GUIDE. US Department of Commerce Technology Administration, National Institute of Standards and Technology (NIST), Gaithersburg, MD, 20899.

Martin, A.E., Kaseer, F., Arambula-Mercado, E., Bajaj, A., Cucalon, L.G., Yin, F., Chowdhury, A., Epps, J., Glover, C., Hajj, E.Y., and Morian, N., 2019. Evaluating the effects of recycling agents on asphalt mixtures with high RAS and RAP binder ratios. NCHRP Research Report, (927).

National Institute of Environmental Health Sciences (NIEHS), 2018. All About Phthalates. [Online] Available at: https://www.niehs.nih.gov/research/supported/translational/peph/podcasts/2015/mar23_phthalates/index.cfm.

National Institute of Environmental Health Sciences (NIEHS), 2020. Bisphenol A (BPA). [Online] Available at: https://www.niehs.nih.gov/health/topics/agents/sya-bpa/index.cfm.

Osborn, L., 2015. Study Comparing Asphalt Emissions from Traditional Asphalt Mix and a Mix Containing Rejuvenator. A Report Submitted to the National Center for Asphalt Technology.

Planche, J.P., 2020. Addressing Impacts of Changes in Asphalt Binder Formulation and Manufacture on Pavement Performance through Changes in Asphalt Binder Specifications. NCHRP 9-60 Draft Final Report.

Plastics Industry Association (PLASTICS), 2018. Literature Review: Using Recycled Plastics for Compounding and Additives.

Rangelov, M., Dylla, H., and Sivaneswaran, N., 2021. Life-Cycle Assessment of Asphalt Pavements with Recycled Post-Consumer Polyethylene. Transportation Research Record, p.03611981211033862.

Ranta-Korpi, M., Vainikka, P., Konttinen, J., Saarimaa, A., and Rodriguez, M., 2014. Ash forming elements in plastics and rubbers. The VTT publication series, 186.

Remtulla, A. and Halligan, S., 2021. Interim guidelines for the use of recycled waste plastic in local government road surfacing applications (No. AP-G96-21).

Serfass, J.P., Bauduin, A., and Garnier, J.F., 1992. High modulus asphalt mixes-laboratory evaluation, practical aspects and structural design. In International Conference on Asphalt Pavements, 7th, 1992, Nottingham, United Kingdom (Vol. 1).

Shbeeb, M.T., 2007. The use of polyethylene in hot asphalt mixtures. American Journal of Applied Sciences, 4(6), pp.390-396.

Shenoy, A.V., Chattopadhyay, S., and Nadkarni, V.M., 1983. From melt flow index to rheogram. Rheologica Acta, 22(1), pp.90-101.

Soroushian, P., Plasencia, J., and Ravanbakhsh, S., 2003. Assessment of reinforcing effects of recycled plastic and paper in concrete. Materials Journal, 100(3), pp.203-207.

Stroup-Gardiner, M. and Lange, C.R., 2005. Comparison of laboratory-generated and field-obtained HMA VOCs with odour potential. The International Journal of Pavement Engineering, 6(4), pp.257-263.

Stuart, K.D., Mogawer, W.S., and Romero, P., 2000. Validation of asphalt binder and mixture tests that measure rutting susceptibility using the accelerated loading facility (No. FHWA-RD-99-204,).

Vrtis, M., 2020. NCAT/MnROAD Cracking Group Update. Fall 2020 Sponsor Meeting, Presented on September 23, 2020.

West, R., 2020. Cracking Group Experiment Update. Fall 2020 Sponsor Meeting, Presented on September 22, 2020.

White, G., 2019. Evaluating recycled waste plastic modification and extension of bituminous binder for asphalt. In Eighteenth Annual International Conference on Pavement Engineering, Asphalt Technology and Infrastructure, Liverpool, England, United Kingdom.

Williams, B. A., Willis, J. R., and Ross, T. C., 2019. Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage, s.l.: NAPA Information, 9th Annual Survey.

Willis, R., Yin, F., and Moraes, R., 2020. Recycled Plastics in Asphalt Part A: State of the Knowledge.

Yin, F. and West, R.C., 2021. Balanced Mix Design Resource Guide (No. IS-143).

Yin, F., Moraes, R., and Anand, A., 2020. Recycled Plastics in Asphalt Part B: Literature Review.

Yin, F., Moraes, R., Fortunatus, M., Tran, N., Elwardany, M.D., and Planche J.P., 2020. Performance Evaluation and Chemical Characterization of Asphalt Binders and Mixtures Containing Recycled Polyethylene. A Report Submitted to the Plastics Industry Association. [Online] Available at : https://www.plasticsindustry.org/sites/default/files/PLASTICS%20NEMO%20Film%20Phase%20III%20Final%20Report%2003102020.pdf.

Zhou, F., Hu, S., and Newcomb, D., 2020. Development of a performance-related framework for production quality control with ideal cracking and rutting tests. Construction and Building Materials, 261, p.120549.

APPENDIX A. ANNOTATED BIBLIOGRAPHY

This appendix summarizes a comprehensive literature review on the use of recycled plastics in asphalt, which includes more than 150 research reports, journal articles, trade publications, newsletter and magazine articles, technical guidance, and personal email communications, all written in English or Spanish. For ease of reference, the review studies are organized chronologically and then alphabetically by the title of the study. Review studies by the same authors and with similar findings are grouped together for discussion. A guidance table is provided on pages A-2 through A-12 to indicate the year of publication, authors, title, type of recycled plastics used, method of incorporating recycled plastics in asphalt mixtures, and overall scope of the review studies. Starting on page A-13, a summary table and a synthesis are provided for each individual review study to discuss its scope of work and documented findings and recommendations.

Table 1. A Guidance Table of Literature Review Studies

Year	Authors	Title	Type of Recycled Plastics Used	Method of Incorporating Recycled Plastics	Scope of Work	Page Number
1991	Maupin	Evaluation of Novophalt as an Additive in Asphalt	PE	Wet Process (Novophalt®)	Field Project, Laboratory Testing (Binder, Mixture)	13-14
1993	Maupin	Evaluation of a Modified Asphalt: Novophalt				
1991	Little	Performance Assessment of Binder-Rich Polyethylene-Modified Asphalt Concrete Mixtures (Novophalt)	LDPE	Wet Process (Novophalt®)	Field Project, Laboratory Testing (Mixture)	15
1992	Little	Analysis of the Influence of Low Density Polyethylene Modification (Novophalt) of Asphalt Concrete on Mixture Shear Strength and Creep Deformation Potential	LDPE	Wet Process (Novophalt®)	Laboratory Testing (Mixture)	16
1992	Serfass et al.	High Modulus Asphalt Mixes - Laboratory Evaluation, Practical Aspects and Structural Design	PE	Dry Process	Laboratory Testing (Mixture), Field Project	17
1993	Little	Enhancement of Asphalt Concrete Mixtures to Meet Structural Requirements through the Addition of Recycled Polyethylene	LDPE	Wet Process (Novophalt®)	Laboratory Testing (Mixture)	18
1993	Williams	Field Performance Evaluation of Novophalt Modified Asphalt Concrete	PE	Wet Process (Novophalt®)	Field Project	19-20
1993	Liang and Hesp	In Situ Steric Stabilization of Polyethylene Emulsions in Asphalt Binders for Hot-Mix Pavement Applications	HDPE, LLDPE	Asphalt-Plastic Emulsion	Laboratory Testing (Binder)	21-22
1993	Daly et al.	Preparation and Characterization of Asphalt-Modified Polyethylene Blends	HDPE, LDPE	Wet Process	Laboratory Testing (Binder)	23-24
1993	Flynn	Recycled Plastic Finds Home in Asphalt Binder	PE	Wet Process	Field Project	25-26
1994	Harbinson and Remtulla	The Development and Performance of an Environmentally Responsible Modified Binder	LDPE	Wet Process (Polyphalt®)	Laboratory Testing (Binder, Mixture)	27
1997	Serfass et al.	Properties and New Developments of High Modulus Asphalt Concrete	PE	Dry Process	Laboratory Testing (Mixture), Field Project	28
1998	Cernuda et al.	Polyethylene Modified Binders in the Chirivel Section (Almeria) – Province Limit with Murica A-92 North	PE	Wet Process	Laboratory Testing (Binder, Mixture)	29

1999	General Directorate of Military Works	Al KHARKHEER Airport Project Design and Evaluation of Novophalt Modified Binder and Asphalt Mix	LDPE	Wet Process (Novophalt®)	Field Project, Laboratory Testing (Mixture)	30-31
1999	Lalib and Maher	Recycled Plastic Fibers for Asphalt Mixtures	PP	Dry Process	Laboratory Testing (Mixture)	32
2000	Tuncan et al.	Reuse of Crumb Rubber and Plastic on Hot-Mixed Asphalt Concrete	LDPE	Wet Process	Laboratory Testing (Mixture)	33
2000	Yousefi et al.	Composite Asphalt Binders: Effect of Modified RPE on Asphalt	PE	Wet Process	Laboratory Testing (Binder)	34
2000	Stuart et al.	Validation of Asphalt Binder and Mixture Tests that Measure Rutting Susceptibility	LDPE	Wet Process (Novophalt®)	Accelerated Pavement Testing, Laboratory Testing (Mixture)	35-37
2002	Gao et al.	Improved Storage Stability of LDPE/SBS Blends Modified Asphalts	LDPE	Wet Process	Laboratory Testing (Binder)	38-39
2002	ROADSTONE Dublin Ltd.	NOVOPHALT Polymer Modified Asphalt Design for Casement Aerodrome at BALDONNEL	LDPE	Wet Process (Novophalt®)	Laboratory Testing (Mixture)	40
2002	Kamada and Yamada	Utilization of Waste Plastics in Asphalt Mixtures	PE, PP	Dry Process	Laboratory Testing (Mixture)	41
2003	Yousefi	Rubber-polyethylene Modified Bitumens	HDPE, LDPE, LLDPE	Wet Process	Laboratory Testing (Binder)	42
2004	Hinislioglu and Agar	Use of Waste High Density Polyethylene as Bitumen Modifier in Asphalt Concrete Mix	HDPE	Wet Process	Laboratory Testing (Mixture)	43
2005	Polacco et al.	Asphalt Modification with Different Polyethylene-based Polymers	PE	Wet Process	Laboratory Testing (Binder)	44
2005	Hinislioglu et al.	Effects of High-density Polyethylene on the Permanent Deformation of Asphalt Concrete	HDPE	Wet Process	Laboratory Testing (Mixture)	45
2005	Hussein et al.	Influence of Mw of LDPE and Vinyl Acetate Content of EVA on the Rheology of Polymer Modified Asphalt	LDPE	Wet Process	Laboratory Testing (Binder)	46
2005	Hassani et al.	Use of Plastic Waste (Poly-ethylene Terephthalate) in Asphalt Concrete Mixture as Aggregate Replacement	PET	Dry Process	Laboratory Testing (Mixture)	47
2006	Widyatmok et al.	Added Value Potential of Processed Plastic Aggregate and ISF Slag in Asphalt	Not Specified	Dry Process	Laboratory Testing (Mixture)	48

2006	Gonzalez et al.	Bitumen/Polyethylene Blends: using m-LLDPEs to Improve Stability and Viscoelastic Properties	HDPE, LLDPE	Wet Process	Laboratory Testing (Binder)	49
2006	Ho et al.	Study of Recycled Polyethylene Materials as Asphalt Modifiers	PE, LDPE	Wet Process	Laboratory Testing (Binder)	50
2007	Awward and Shbeeb	The Use of Polyethylene in Hot Asphalt Mixtures	HDPE, LDPE	Dry Process	Laboratory Testing (Mixture)	51
2008	Casey et al.	Development of a Recycled Polymer Modified Binder for Use in Stone Mastic Asphalt	PE, PP, PVC, PET	Wet Process	Laboratory Testing (Binder, Mixture)	52-53
2008	Al-Taher et al.	Evaluation of Asphalt Pavements Constructed using Novophalt	PE	Wet Process (Novophalt®)	Laboratory Testing (Mixture)	54-55
2008	Fuentes-Auden et al.	Evaluation of Thermal and Mechanical Properties of Recycled Polyethylene Modified Bitumen	LDPE, LLDPE, PP	Wet Process	Laboratory Testing (Binder)	56-57
2008	Central Pollution Control Board	Performance Evaluation of Polymer Coated Bitumen Built Roads	PE, PP, PS	Dry Process	Field Project	58-60
2009	Al-Hadidy and Tan	Effect of Polyethylene on Life of Flexible Pavements	LDPE	Wet Process	Laboratory Testing (Binder, Mixture), Pavement Design	61-62
2010	Aschuri and Woodward	Modification of a 14mm Asphalt Concrete Surfacing Using Rap and Waste HDPE Plastic	HDPE	Wet Process	Laboratory Testing (Mixture)	63
2011	Punith and Veeraragavan	Behavior of Reclaimed Polyethylene Modified Asphalt Cement for Paving Purpose	LDPE	Wet Process	Laboratory Testing (Binder)	64
2011	Sangita et al.	Effect of Waste Polymer Modifier on the Properties of Bituminous Concrete Mixes	PE	Dry Process	Laboratory Testing (Mixture)	65
2011	Moatasim et al.	Laboratory Evaluation of HMA with High Density Polyethylene as a Modifier	HDPE	Wet Process	Laboratory Testing (Mixture)	66
2011	Ahmadinia et al.	Using Waste Plastic Bottles as Additive for Stone Mastic Asphalt	PET	Dry Process	Laboratory Testing (Mixture)	67
2012	Vasudevan et al.	A Technique to Dispose Waste Plastics in an Ecofriendly Way – Application in Construction of Flexible Pavements	PE, PP, PS	Dry Process	Laboratory Testing (Mixture), Field Project, Cost Analysis	68
2012	Villegas et al.	Use of Recycled Material from the Banana Bags Protection as an Improver of the Asphalt Properties and Reduction of the Plastic Waste. Costa Rica and Colombian Experience	PE	Wet Process	Laboratory Testing (Binder)	69

2012	Rongali et al.	Laboratory Investigation on Use of Fly Ash Plastic Waste Composite in Stone Matrix Asphalt	Not Specified	Dry Process	Laboratory Testing (mixture)	70
2012	Villegas-Villegas et al.	Recycling of Banana Production Waste Bags in Bitumens: A Green Alternative	HDPE	Wet Process	Laboratory Testing (Binder, Mixture)	71-72
2012	Gawande et al.	Utilization of Waste Plastic in Asphalting of Roads	Not Applicable	Not Applicable	Literature Review	73
2013	Vargas et al.	Asphalt/Polyethylene Blends: Rheological Properties, Microstructure and Viscosity Modeling	HDPE, LDPE, PE	Wet Process	Laboratory Testing (Binder)	74
2013	Aguiar-Moya et al.	Use of Waste Products as Bitumen Modifiers in Costa Rica	PE, PP, PS	Wet Process	Laboratory Testing (Binder)	75
2013	Khurshid et al.	Comparative Analysis of Conventional and Waste Polyethylene Modified Bituminous Mixes	HDPE	Wet Process, Dry Process	Laboratory Testing (Mixture), Cost Analysis	76
2013	Indian Roads Congress	Guidelines for the Use of Waste Plastic in Hot Bituminous Mixes (Dry Process) in Wearing Courses	HDPE, LDPE, PU, PET	Dry Process	Agency Specification	77
2013	Costa et al.	Incorporation of Waste Plastic in Asphalt Binders to Improve their Performance in the Pavement	HDPE, LDPE	Wet Process	Laboratory Testing (Binder)	78-79
2013	Khan et al.	Rutting performance of Polyethylene, Lime and Elvaloy modified Asphalt Mixes	LDPE	Dry Process	Laboratory Testing (Mixture)	80
2013	Moghaddam et al.	Utilization of Waste Plastic Bottles in Asphalt Mixture	PET	Dry Process	Laboratory Testing (Mixture)	81
2014	Wang et al.	Crumb Tire Rubber and Polyethylene Mutually Stabilized in Asphalt by Screw Extrusion	HDPE	Wet Process	Laboratory Testing (Binder)	82-83
2014	Ahmed and AL-Harbi	Effect of Density of the Polyethylene Polymer on the Asphalt Mixtures	HDPE, LDPE	Wet Process	Laboratory Testing (Mixture)	84
2014	Nejada et al.	Effect of High-Density Polyethylene on the Fatigue and Rutting Performance of Hot Mix Asphalt – A Laboratory Study	HDPE	Wet Process	Laboratory Testing (Mixture)	85
2014	Abd-Allah et al.	Effect of Using Polymers on Bituminous Mixtures Characteristics in Egypt	HDPE, LDPE, PVC	Wet Process	Laboratory Testing (Binder, Mixture)	86
2014	Moghaddam et al.	Evaluation of Permanent Deformation Characteristics of Unmodified and Polyethylene Terephthalate Modified Asphalt Mixtures using Dynamic Creep Test	PET	Dry Process	Laboratory Testing (Mixture)	87-88

2015	Moghaddam et al.	Estimation of the Rutting Performance of Polyethylene Terephthalate Modified Asphalt Mixtures by Adaptive Neuro-fuzzy Methodology				
2014	Moghaddam et al.	Experimental Characterization of Rutting Performance of Polyethylene Terephthalate Modified Asphalt Mixtures Under Static and Dynamic Loads	PET	Dry Process	Laboratory Testing (Mixture)	89
2014	Gürü et al.	An Approach to the Usage of Polyethylene Terephthalate (PET) Waste as Roadway Pavement Material	PET	Wet Process	Laboratory Testing (Binder)	90
2014	Modarres and Hamedi	Effect of Waste Plastic Bottles on the Stiffness and Fatigue Properties of Modified Asphalt Mixes	PET	Dry Process	Laboratory Testing (Mixture)	91
2014	Fang et al.	Pavement Properties of Asphalt Modified with Packaging-Waste Polyethylene	PE	Wet Process	Laboratory Testing (Binder)	92
2014	Fang et al.	Preparation and Properties of Asphalt Modified with a Composite Composed of Waste Package Poly (vinyle chloride) and Organic Montmorillonite	PVC	Wet Process	Laboratory Testing (Binder)	93
2014	Melbouci et al.	Study of Strengthening of Recycled Asphalt Concrete by Plastic Aggregates	PE	Dry Process	Laboratory Testing (Mixture)	94
2014	Ali et al.	Sustainability Assessment of Bitumen with Polyethylene as Polymer	LDPE	Wet Process	Laboratory Testing (Binder)	95
2015	Diefenderfer and Mcghee	Installation and Laboratory Evaluation of Alternatives to Conventional Polymer Modification for Asphalt	SBS-PE Copolymer	Wet Process	Laboratory Testing (Binder), Field Project	96
2015	Moghaddam et al.	Stiffness Modulus of Polyethylene Terephthalate Modified Asphalt Mixture: A Statistical Analysis of the Laboratory Testing Results	PET	Dry Process	Laboratory Testing (Mixture)	97
2015	Yu et al.	Storage Stability and Rheological Properties of Asphalt Modified with Waste Packaging Polyethylene and Organic Montmorillonite	LDPE/LLDPE Blend	Wet Process	Laboratory Testing (Binder)	98
2016	Khan et al.	Asphalt Design using Recycled Plastic and Crumb-rubber Waste for Sustainable Pavement Construction	HDPE, LDPE	Wet Process	Laboratory Testing (Binder)	99
2016	Angelone et al.	A Comparative Study of Bituminous Mixtures with Recycled PE Added by Dry and Wet Processes	PE	Dry Process, Wet Process	Laboratory Testing (Binder, Mixture)	100
2016	Ahmedzade et al.	Irradiated Recycled High Density Polyethylene Usage as a Modifier for Bitumen	PE	Wet Process	Laboratory Testing (Binder)	101
2016	Lastra-González et al.	Comparative Analysis of the Performance of Asphalt Concretes Modified by Dry Way with Polymeric Waste	PE, PP, PS	Dry Process	Laboratory Testing (Mixture)	102

2016	Cuadri et al.	Formulation and Processing of Recycled-low-density-polyethylene-modified Bitumen Emulsions for Reduced-temperature Asphalt Technologies	LDPE/LLDPE Blend	Asphalt-Plastic Emulsion	Laboratory Testing (Binder)	103
2016	Angelone et al.	Green Pavements: Reuse of Plastic Waste in Asphalt Mixtures	PE, PP	Dry Process	Laboratory Testing (Mixture)	104-105
2016	Brożyna and Kowalski	Modification of Asphalt Binders by Polyethylene-type Polymers	HDPE, LDPE, LLDPE	Wet Process	Laboratory Testing (Binder)	106
2016	Sojobi et al.	Recycling of Polyethylene Terephthalate (PET) Plastic Bottle Wastes in Bituminous Asphaltic Concrete	PET	Dry Process	Laboratory Testing (Binder, Mixture)	107
2016	Usman et al.	Reinforcement of Asphalt Concrete Mixture using Recycle Polyethylene Terephthalate Fiber	PET	Dry Process	Laboratory Testing (Mixture)	108
2017	Bajpai et al.	A Study on the Plastic Waste Treatment Methods for Road Construction	PP	Dry Process	Laboratory Testing (mixture)	119
2017	Singh et al.	Properties of Asphalt Binder and Asphalt Concrete Containing Waste Polyethylene	PE	Dry Process	Laboratory Testing (Binder, Mixture)	110
2017	Vila-Cortavitarte et al.	Analysis of the Influence of using Recycled Polystyrene as a Substitute for Bitumen in the Behaviour of Asphalt Concrete Mixtures	PS	Dry Process	Laboratory Testing (Mixture), Environmental Impact Assessment	111
2017	Dehghan and Modarres	Evaluating the Fatigue Properties of Hot Mix Asphalt Reinforced by Recycled PET Fibers using 4-point Bending Test	PET	Dry Process	Laboratory Testing (Mixture)	112
2017	Nejad et al.	Effect of Cross-linkers on the Performance of Polyethylene-modified Asphalt Binders	HDPE	Wet Process	Laboratory Testing (Binder)	113
2017	Reddy and Venkatasubbaiah	Effects of High-Density Polyethylene and Crumb Rubber Powder on Properties of Asphalt Mix	HDPE	Wet Process, Dry Process	Laboratory Testing (Binder, Mixture)	114
2017	Jana et al.	Performance Evaluation of Hot Mix Asphalt Concrete by Using Polymeric Waste Polyethylene	LDPE	Wet Process	Laboratory Testing (Binder)	115
2017	Dalhat and Al-Abdul Wahhab	Performance of Recycled Plastic Waste Modified Asphalt Binder in Saudi Arabia	LDPE, HDPE, PP	Wet Process	Laboratory Testing (Binder), Pavement Design	116-117
2017	Badejo et al.	Plastic Waste as Strength Modifiers in Asphalt for A Sustainable Environment	PET	Dry Process	Laboratory Testing (Mixture)	118

2017	Bala et al.	Rheological Properties Investigation of Bitumen Modified with Nanosilica and Polyethylene Polymer	LLDPE	Wet Process	Laboratory Testing (Binder)	119
2017	Al-Abdul Wahhab et al.	Storage Stability and High-temperature Performance of Asphalt Binder Modified with Recycled Plastic	HDPE, LDPE, PP	Wet Process	Laboratory Testing (Binder)	120
2017	Anand and Sathya	Use of Plastic Waste in Bituminous Pavement	Not Specified	Wet Process, Dry Process	Laboratory Testing (Binder, Mixture)	121
2017	Appiah et al.	Use of Waste Plastic Materials for Road Construction in Ghana	HDPE, PP	Wet Process	Laboratory Testing (Binder)	122
2017	Chakraborty and Mehta	Utilization & Minimization of Waste Plastic in Construction of Pavement: A Review	Not Applicable	Not Applicable	Literature Review	123
2018	Tilley	Bags, bottles being transformed into roadways	Proprietary Product	Not Specified	Field Project	124
2018	López et al.	Reuse of Agricultural Plastic Wastes for the Manufacturing of Roads Bituminous Mixtures, using the "Dry Way" Methodology	PE	Dry Process	Laboratory Testing (Mixture), Field Project	125
2018	Leng et al.	Value-added Application of Waste PET Based Additives in Bituminous Mixtures Containing High Percentage of Reclaimed Asphalt Pavement (RAP)	PET	Wet Process	Laboratory Testing (Binder)	126
2018	Paben	Dow joins project building roads with recycled LDPE	LDPE	Dry Process	Field Project	127
2018	Padhan and Screeram	Enhancement of Storage Stability and Rheological Properties of Polyethylene (PE) Modified Asphalt using Cross Linking and Reactive Polymer Based Additives	LDPE	Wet Process	Laboratory Testing (Binder)	128-129
2018	Amirkhanian	Investigations of Rheological Properties of Asphalt Binders Modified with Scrap Polyethylenes	PE	Wet Process	Laboratory Testing (Binder)	130
2018	Zhang et al.	Preparation Methods and Performance of Modified Asphalt Using Rubber–Plastic Alloy and Its Compounds	LDPE	Wet Process	Laboratory Testing (Binder)	131
2018	Roads & Infrastructure Magazine	Recycled Plastic used in Airport Asphalt	Proprietary Product	Not Specified	Field Project	132
2018	Fulton Hogan	Trial recycles plastic containers into asphalt				
2018	White and Reid	Recycled Waste Plastic for Extending and Modifying Asphalt Binders	Proprietary Product	Dry Process	Laboratory Testing (Binder, Mixture), Cost Analysis	133
2019	El-Naga, and Ragab	Benefits of Utilization the Recycle Polyethylene Terephthalate Waste Plastic Materials as a Modifier to Asphalt Mixtures	PET	Wet Process, Dry Process	Laboratory Testing (Binder, Mixture), Pavement Design	134

2019	CBC News	Burnside parking lot partially paved with plastic	Proprietary Product	Not Specified	Field Project	135
2019	Dow Corporate	Dow Completes Roads Improved with Recycled Plastic	LLDPE	Wet Process	Field Project	136
2019	www.ConstructionEquipmentGuide.com	Dow Mixes Post-Consumer Plastic into Asphalt Roads				
2019	Dow Corporate	Dow Incorporates Recycled Plastic into Michigan Roads and Parking Lots	Not Specified	Wet Process	Field Project	137
2019	AMAP	Recycled Plastic in Modified Asphalt				
2019	White	Evaluating Recycled Waste Plastic Modification and Extension of Bituminous Binder for Asphalt	Proprietary Product	Wet Process	Laboratory Testing (Binder, Mixture)	138
2019	Peters	Los Angeles is testing 'plastic asphalt' that makes it possible to recycle roads	PET	Plastic Synthetic Binder	Field Project	139
2019	Tappeiner	Novophalt Field Project List	PE	Wet Process (Novophalt®)	Field Project	140
2019	US San Diego News Center	On the Road to Solving our Plastic Problem	Proprietary Product	Not Specified	Field Project	141
2019	McCarthy	The First Road Made from Plastic Waste Was Just Finished in the US				
2019	CBC News	Parking lot at new Sobeys in Timberlea largely made from recycled plastics	Not Specified	Not Specified	Field Project	142
2019	Yin et al.	Performance Evaluation and Chemical Characterization of Asphalt Binders and Mixtures Containing Recycled Polyethylene	PE	Wet Process	Laboratory Testing (Binder, Mixture)	143-144
2019	Dalhat et al.	Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification	HDPE, LDPE, PP, PVC, PS	Wet Process, Dry Process	Laboratory Testing (Binder, Mixture)	145-146
2019	Yin et al.	Storage Stability Testing of Asphalt Binders Containing Recycled Polyethylene Materials (Phase II-B Study)	PE	Wet Process	Laboratory Testing (Binder)	147-149
2018	Yin and Moraes	Storage Stability Testing of Asphalt Binders Containing Recycled Polyethylene Materials				
2019	Reynolds	This company is using recycled plastic mile bottles to repave roads in South Africa	HDPE	Wet Process	Field Project	150

2019	Martin-Alfonso et al.	Use of Plastic Wastes from Greenhouse in Asphalt Mixes Manufactured by Dry Process	LDPE	Wet Process, Dry Process	Laboratory Testing (Mixture)	151
2019	Sasidharan et al.	Using Waste Plastics in Road Construction	Not Applicable	Not Applicable	Literature Review	152-153
2019	Chin and Damen	Viability of Using Recycled Plastics in Asphalt and Sprayed Sealing Applications	Not Applicable	Not Applicable	Literature Review	154-155
2019	Mashaan et al.	Waste Plastic as Additive in Asphalt Pavement Reinforcement: A Review	Not Applicable	Not Applicable	Literature Review	156-157
2019	White and Magee	Laboratory Evaluation of Asphalt Containing Recycled Plastic as a Bitumen Extender and Modifier	PE	Wet Process	Laboratory Testing (Binder, Mixture)	158
2019	White and Reid	Recycled Waste Plastic Modification of Bituminous Binder	PE	Wet Process	Laboratory Testing (Binder)	159-160
2019	Casaux et al.	Safety and Sustainability in Road Construction. Study of the Use of Recycled Plastics to Reduce Rutting in Asphalt Mixtures (Seguridad y Sustentabilidad en la construcción de carreteras. Estudio del empleo de plásticos reciclados para la reducción del ahuellamiento en mezclas asfálticas	PE	Dry Process	Laboratory Testing (Mixture)	161
2019	Mazouz and Merbouh	The Effect of Low-Density Polyethylene Addition and Temperature on Creep-recovery Behavior of Hot Mix Asphalt	LDPE	Dry Process	Laboratory Testing (Mixture)	162
2019	Taherkhani and Arshadi	Investigating the Mechanical Properties of Asphalt Concrete Containing Waste Polyethylene Terephthalate	PET	Dry Process	Laboratory Testing (Mixture)	163
2020	Tappeiner	Information Related to the BRITE EURAM Project	PE	Not Specified	Laboratory Testing (Binder, Mixture), Field Project	164-165
2020	Polyphalt, Inc.	Licensing Process Technology for Polymer Modified Bitumen	PE	Wet Process (Polyphalt®)	Product Introduction	166-167
2020	Polyphalt, Inc.	Ontario Asphalt Technology Takes on the World				
2020	Polyphalt, Inc.	Welcome to Polyphalt Inc.				
2020	Nizamuddin et al.	Recycled Plastic as Bitumen Modifier: The Role of Recycled Linear Low Density Polyethylene in the Modification of Physical, Chemical and Rheological Properties of Bitumen	LLDPE	Wet Process	Laboratory Testing (Binder)	168-169
2020	Masad et al.	A Review of Asphalt Modification Using Plastics: A Focus on Polyethylene	PE	Not Applicable	Literature Review	170

2020	Santos et al.	Recycling Waste Plastics in Roads: A Life-cycle Assessment Study using Primary Data	Not Specified	Wet Process, Dry Process	Environmental Impact Assessment	171
2020	White and Hall	Laboratory Comparison of Wet-mixing and Dry-mixing of Recycled Waste Plastic for Binder and Asphalt Modification	PE	Wet Process, Dry Process	Laboratory Testing (Binder, Mixture)	172
2020	Zhang et al.	Experimental Exploration of Influence of Recycled Polymer Components on Rutting Resistance and Fatigue Behavior of Asphalt Mixtures	PE	Dry Process	Laboratory Testing (Mixture)	173
2020	Biswas et al.	Performance Comparison of Waste Plastic Modified versus Conventional Bituminous Roads in Pune City: A Case Study	Not Specified	Not Specified	Field Project	174
2020	Padhan et al.	Compound Modification of Asphalt with Styrene-butadiene-styrene and Waste Polyethylene Terephthalate Functionalized Additives	PET	Wet Process	Laboratory Testing (Binder)	175
2020	White	A Synthesis on the Effects of Two Commercial Recycled Plastics on the Properties of Bitumen and Asphalt	PE	Wet Process	Laboratory Testing (Binder, Mixture)	176
2020	Ibrahim Al Helo et al.	Effect of Laboratory Aging on Moisture Susceptibility of Polymer-modified Bituminous Mixtures	PET	Dry Process	Laboratory Testing (Mixture)	177
2020	Esfandabad et al.	Fracture and Mechanical Properties of Asphalt Mixtures Containing Granular Polyethylene Terephthalate (PET)	PET	Dry Process	Laboratory Testing (Mixture)	178
2020	Joohari and Giustozzi	Chemical and High-temperature Rheological Properties of Recycled Plastics-polymer Modified Hybrid Bitumen	PE	Wet Process	Laboratory Testing (Binder)	179
2020	Lin et al.	Use of Recycled Plastic in Local Roads in Regional Areas	Not Applicable	Not Applicable	Technical Guidance	180-181
2021	Kakar et al.	Analysis of Waste Polyethylene (PE) and its By-products in Asphalt Binder	PE	Wet Process	Laboratory Testing (Binder)	182-183
2021	Giustozzi and Boom	Use of Road-grade Recycled Plastics for Sustainable Asphalt Pavements: Overview of the Recycled Plastic Industry and Recycled Plastic Types	Not Applicable	Not Applicable	Technical Guidance	184-185
2021	Zou et al.	Feasibility Study on Recycled Vegetable Oil Waste and Recycled Polyethylene for the Modification of Aged Asphalt	LDPE	Wet Process	Laboratory Testing (Binder)	186
2021	Remtulla and Halligan	Interim Guidelines for the Use of Recycled Waste Plastic in Local Government Road Surfacing Applications	Not Applicable	Not Applicable	Technical Guidance	187-188
2021	Nizamuddin et al.	Recycling of Low-value Packaging Films in Bitumen Blends: A Grey-based Multi Criteria Decision Making	PE	Wet Process	Laboratory Testing (Binder),	189-190

		Approach considering a Set of Laboratory Performance and Environmental Impact Indicators			Environmental Impact Assessment	
2021	Celauro et al.	Preliminary Evaluation of Plasmix Compound from Plastics Packaging Waste for Reuse in Bituminous Pavements	HDPE, LDPE, LLDPE, PS, PP, PET	Wet Process, Dry Process	Laboratory Testing (Binder, Mixture)	191-192

“Evaluation of Novophalt as an Additive in Asphalt” by G.W. Maupin as *Virginia Transportation Research Council Report 91-IR6*, 1991.

“Evaluation of a Modified Asphalt: Novophalt” by G.W. Maupin as *Virginia Transportation Research Council Report 94R-9*, 1993.

Authors	G.W. Maupin (Virginia Transportation Research Council)
Sponsor	Virginia Department of Transportation
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	5 Percent by Weight of Asphalt Binder
Scope	Field Project, Laboratory Binder Testing, Laboratory Mixture Testing

This report documents the installation, test results, and preliminary field performance of a test section constructed using Novophalt®. The test section, sponsored by the Virginia Department of Transportation (VDOT), was part of a new construction project in the Salem District. The test section consisted of two pavement sections of Novophalt® mixtures and two sections of unmodified control mixtures. Both mixtures were placed as a 1.5-inch asphalt surface layer on top of a 6.0-inch asphalt base layer. The Novophalt® binder was produced by modifying an AC-20 asphalt binder with 5 percent polyethylene by weight of asphalt binder. Both mixtures were designed using the Marshall mix design procedure with a 75-blow compactive effort and 4.0 percent target air voids, which resulted in an optimum binder content of 5.0 percent for the Novophalt® mixture and 5.2 percent for the control mixture. The mixtures had a maximum aggregate size of 12.5 mm. During production, a patented blending unit was set up at the asphalt plant for the formulation of Novophalt® binder, but no special equipment was required to place the Novophalt® mixture. Construction of both pavement sections went well with no problems reported.

During construction, virgin binder and plant mix were sampled and tested in the laboratory. The Novophalt® binder had significantly higher viscosity at 60°C and 135°C than the control AC-20 binder. The Novophalt® mixture had higher voids in total mix (VTM) and lower voids filled with asphalt (VFA) and voids in mineral aggregates (VMA) than the control mixture; nevertheless, both mixtures satisfied VDOT’s volumetric requirements. Surprisingly, no significant difference in Marshall stability was observed between the two mixtures. Both pavement sections had similar in-place air voids (approximately 10 percent) after construction. However, in-place density decreased to 3 percent for the Novophalt® section and 6 percent for the control section after one summer in-service. Both mixtures showed low shear strength, high gyratory stability index (GSI), and low predicted voids in the gyratory testing machine (GTM) test, which indicated possible over-densification and instability issues in the field. Resilient modulus and indirect tensile tests showed that the Novophalt® mixture was stiffer and more stable than the control mixture; however, no difference was observed in the creep test between the two mixtures. Field rut depth measurements taken 10 months after construction showed severe rutting in the Novophalt® section, which later was realized to be confined to the base layer due to a lack of production quality. Therefore, no confirmative conclusion was made as to whether the Novophalt® mixture could perform better than the control mixture. Continued monitoring of both pavement sections was recommended to compare their long-term performance. The typical added cost for using a Novophalt® binder was approximately $5 to $6 per ton of mixture. Using an average cost of $25 to $30 per ton of mixture, a 20 percent increase in pavement service life would be needed to justify the additional cost; however, no cost-benefit analysis was conducted due to a lack of good performance data.

"Performance Assessment of Binder-Rich Polyethylene-Modified Asphalt Concrete Mixtures (Novophalt)" by D.N. Little in *Transportation Research Record*, 1991.

Authors	D.N. Little (Texas A&M University)
Sponsor	Unknown
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	5 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing, Field Project

This study focused on the performance assessment of binder-rich polyethylene-modified (Novophalt®) asphalt mixtures placed in a runway reconstruction project at the William Hobby Airport in Houston, Texas. The existing pavement structure consisted of 4 inches of asphalt overlay on top of a plain Portland cement concrete pavement. The reconstruction called for milling off the existing asphalt layer and replacing it with 7 inches of Novophalt® mixtures. Details about the final job mix formula (JMF) and layer structures of the Novophalt® mixtures were not provided. Before the Novophalt® overlay was placed, a stress-absorbing membrane interlayer was laid to mitigate reflective cracking from the Portland cement concrete. Given the heavy loading of aircraft and the hot Texas summers, the primary structural design criterion of this reconstruction project was permanent deformation. The Novophalt® binder was produced by modifying an AC-20 asphalt binder with 5 percent recycled low-density polyethylene (by weight of asphalt binder) using a patented high-shear blender at the asphalt plant. Two sets of Novophalt® mixtures were tested in the laboratory; one was designed using Marshall and Texas mix design procedures and had an optimum binder content of 4.8 percent, while the other was designed to be a binder-rich mixture with an increased binder content of 5.8 percent. Only the latter was placed in the field. In addition to the Novophalt® mixtures, two unmodified mixtures (using an AC-20 asphalt binder) with 5.0 and 5.8 percent binder contents were tested in the laboratory for performance comparison. Both Novophalt® and unmodified mixtures were subjected to the compressive uniaxial creep compliance test, uniaxial repeated-load permanent deformation test, tensile creep and strength test, and resilient modulus test. Test results indicated that Novophalt® mixtures had significantly better resistance to permanent deformation and densification than the unmodified mixtures, which was attributed to the changes in rheological properties of asphalt binders due to LDPE modification. Despite the low air void content, the binder-rich Novophalt® mixture provided superior resistance to fracture damage and maintained acceptable rutting resistance. The binder-rich Novophalt® overlay performed well two years after construction with no signs of rutting or cracking.

"Analysis of the Influence of Low Density Polyethylene Modification (Novophalt) of Asphalt Concrete on Mixture Shear Strength and Creep Deformation Potential" by D.N. Little in *Polymer Modified Asphalt Binders, American Society for Testing and Materials*, 1992.

Authors	D.N. Little (Texas A&M University)
Sponsor	Unknown
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	4.3, 5.0, and 6.0 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the impact of low-density polyethylene (LDPE) modification (Novophalt®) on the shear strength and creep deformation potential of asphalt mixtures. Two asphalt mixtures with and without LDPE modification were tested; one was produced with crushed limestone (CLS) while the other used river gravel (RG). The CLS mixtures were prepared with two LDPE dosages (4.3 percent and 6.0 percent by weight of asphalt binder) and two asphalt binder contents [the optimum binder content (OBC) corresponding to 4.0 percent design air voids and OBC plus 0.4%]. The RG mixtures had a LDPE dosage of 5.0 percent by weight of asphalt binder and were prepared at the optimum binder content only. Each mixture was subjected to shear strength, uniaxial creep and repeated load permanent deformation, diametral indirect tensile strength and strain at failure, diametral resilient modulus, and indirect tensile creep testing. The evaluation of shear strength potential was based on the octahedral shear stress ratio (OSSR) concept, which was defined as the ratio of induced octahedral shear stress at specific points within the pavement to octahedral shear strength of the pavement layer. In simplified terms, OSSR indicated a factor of safety against shear failure, where a smaller value was desired for better resistance to shear damage. A modified version of the ILLIPAVE program was employed to calculate octahedral normal and shear stresses and then OSSR. OSSR results indicated that LDPE modification significantly improved the mobilized shear strength of asphalt mixtures due to increased mass viscosity and internal friction. From the ILLIPAVE computation analyses, the maximum OSSR in an asphalt pavement constructed using LDPE modified mixtures was over 50 percent lower than that using unmodified mixtures, which indicated significantly better resistance to shear-induced permanent deformation. Creep analysis and cyclic analysis were also conducted to determine the impact of LDPE modification on the permanent deformation potential of asphalt mixtures. Test results indicated similar findings as the OSSR results. LDPE modified mixtures had less permanent strain as compared to unmodified control mixtures, indicating improved resistance to permanent deformation. This improvement became more significant as the level of LDPE modification increased. Finally, the indirect tensile and resilient modulus test results indicated that LDPE modification, due to increased mixture stiffness, enhanced the flexural fatigue properties of asphalt mixtures when tested under a stress-controlled condition.

“High Modulus Asphalt Mixes – Laboratory Evaluation, Practical Aspects and Structural Design” by J.P. Serfass, A. Bauduin, and J.F. Garnier in the *Proceedings of the 7th International Conference on Asphalt Pavements*, 1992.

Authors	J.P. Serfass, A. Bauduin (SCREG Routes, France), and J.F. Garnier (Recherche-Technique-Entreprise, France)
Sponsor	Unknown
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Dry Process
Plastic Dosage	Not Specified
Scope	Laboratory Mixture Testing, Field Project

This study focused on the laboratory characterization of high-modulus (HM) asphalt mixes in France. The HM asphalt mixes were produced with three different methods: using a very hard asphalt binder (with a 10/20 penetration grade), modification with asphaltite, and modification with polyethylene (PE). For the preparation of PE modified HM mixes, PE powder was added into the hot aggregate via the dry process, which was then mixed with the asphalt binder. The dosage of PE used was not provided. The study noted that the wet process could also be used to prepare PE modified HM mixes, but it was not as cost effective and performance effective as the dry process. Mixture compactability evaluation indicated that PE modified HM asphalt mix was more difficult to compact than the other two types of HM mixes, which was due to the high viscosity of PE. As compared to the standard roadbase mix, the PE modified HM mix showed superior stiffness and rutting resistance in the direct tension static modulus test, dynamic modulus test, and wheel-track rut-tester. The PE modified HM mix also outperformed the standard roadbase mix in the flexural trapezoidal beam fatigue test in terms of number of cycles to failure. During production, PE powder was introduced into the mixer in batch mixing plants, or delivered onto the cold feed conveyor or into the recycled asphalt inlet ring in drum mixing plants. Heavy rollers were required for compaction of HM asphalt mixes in order to achieve adequate in-place density. The study also evaluated several field projects of HM asphalt mixes in France. All projects had good in-place density, with a degree of compaction ranging from 94 to 99 percent. Testing of field cores sampled from the projects showed that they had similar stiffness modulus as laboratory-produced mixes. Finally, the study concluded that HM asphalt mixes provided superior structural capacity and rutting resistance and were economically advantageous for urban reconstruction and overlays projects due to the reduction in pavement thickness allowed**.**

"Enhancement of Asphalt Concrete Mixtures to Meet Structural Requirements through the Addition of Recycled Polyethylene" by D.N. Little in *Use of Waste Materials in Hot-Mix Asphalt, American Society for Testing and Materials*, 1993.

Authors	D.N. Little (Texas A&M University)
Sponsor	Unknown
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	4.3, 5.0, and 6.0 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the addition of recycled low-density polyethylene (LDPE) to enhance the structural properties of asphalt mixtures. Asphalt modification with recycled LDPE was achieved using the Novophalt® process. A total of nine mixtures with and without Novophalt® modification were tested, with seven being dense-graded mixtures and the other two being gap-graded stone matrix asphalt (SMA) mixtures. The level of LDPE modification varied from 4.3 to 6.0 percent by weight of asphalt binder among the mixtures. Each mixture was subjected to uniaxial compressive creep, indirect tensile, and controlled displacement fracture propagation testing. In the creep test, LDPE modified mixtures had consistently lower total creep strain, lower log-log slope of the steady state portion of the creep curve, and higher creep stiffness than the unmodified mixtures, indicating enhanced resistance to permanent deformation as a result of LDPE modification. The indirect tensile test results indicated that when tested under a stress-controlled condition, the stiffening effect provided by LDPE modification improved the fatigue life of asphalt mixtures at relatively small strain levels. However, the opposite trend was observed at large strain levels or after the mixtures were artificially aged. LDPE modification also improved the resistance of asphalt mixtures to reflective cracking. This improvement was equivalent to that when other types of polymer modifiers, such as ethylene-vinyl acetate (EVA), styrene-butadiene-styrene (SBS), and styrene–butadiene rubber (SBR), were used for asphalt modification.

“Field Performance Evaluation of Novophalt Modified Asphalt Concrete” by G. Williams as *FHWA/OK Report 93(04)*, 1993.

Authors	G. Williams (Oklahoma Department of Transportation)
Sponsor	Federal Highway Administration
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	4 to 6 Percent by Weight of Asphalt Binder
Scope	Field Project

This report summarizes the findings and recommendations of a research project to evaluate the field performance of a test section constructed in Oklahoma using Novophalt®. The test section was part of a reconstruction project, which called for milling off 4.5 inches of existing pavement and then replacing with a 3-inch asphalt binder layer and a 1.5-inch asphalt surface layer. The existing pavement had severe rutting and shoving issues. The entire reconstruction project included three test sections with different surface mixtures: a polymer-modified control mixture using “Styrelf” [styrene-butadiene-styrene (SBS) block co-polymer] binder, an experimental modified mixture using Novophalt® binder, and an unmodified control mixture using an AC-20 binder. The Novophalt® binder was produced by modifying an AC-20 binder with 4 to 6 percent recycled polyethylene (Figure 1) using a patented high-shear blending unit. As shown in Figure 2, the blending unit was equipped with agitated mixing and storage tanks to prevent phase separation. During production, the blending unit was connected to the asphalt plant with one hose connected to the asphalt intake line and the other hose connected to the return line.

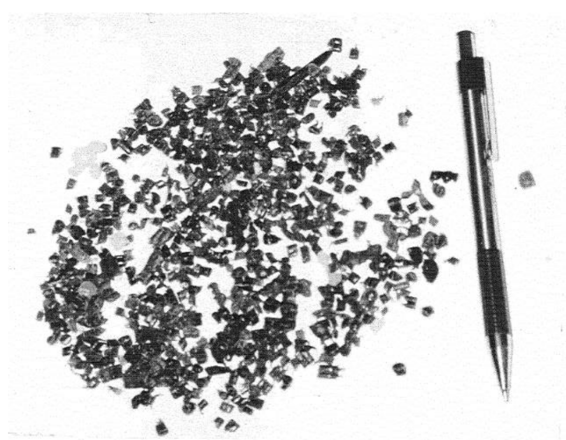


Figure 1. Recycled Polyethylene Pellets used to Produce Novophalt® Binder (Williams, 1993)

Figure 2. Setup of Novophalt® Blending Unit at the Asphalt Plant (Williams, 1993)

Overall, the production and construction of Novophalt® mixtures went well with no issues reported. The contract bid price of the Novophalt® mixture was $200 per ton, which was eight times more expensive than the other two mixtures. This high price of Novophalt® mixture, however, was mainly attributed to the cost of hauling the blending unit a long distance for a relatively small project. Field performance data of the three test sections indicated that the Novophalt® mixture did not perform as well as the polymer-modified control mixture using "Styrelf" binder or the unmodified control mixture. Although rutting was significantly reduced, the Novophalt® section exhibited severe longitudinal and transverse cracking (Figure 3) and would soon require either an overlay or large-scale patching operations for rehabilitation. Given the unsatisfactory performance of this test section, a recommendation was provided to the Oklahoma Department of Transportation to not allow the use of Novophalt® on state projects.

Figure 3. Cracking in the Outside Lane of the Novophalt® Section (Williams, 1993)

“In Situ Steric Stabilization of Polyethylene Emulsions in Asphalt Binders for Hot-Mix Pavement Applications” by Z. Liang and S.A.M. Hesp in *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 1993.

Authors	Z. Liang (University of Toronto, Canada) and S.A.M. Hesp (Queen’s University, Canada)
Sponsor	National Science and Engineering Research Council of Canada, Ontario Centre of Materials Research.
Plastic Type	High-density Polyethylene (HDPE), Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Asphalt-Plastic Emulsion
Plastic Dosage	1 to 7 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study sought to design steric stabilizers for polyethylene (PE) emulsions in asphalt to prevent phase separation during storage. Two asphalt binders with different rheological properties but similar chemical properties were tested; one had an 85/100 penetration grade and the other had a 290-penetration grade. Three types of PE samples were included: virgin linear low-density polyethylene (LLDPE), recycled LLDPE, and virgin high-density polyethylene (HDPE). The virgin LLDPE was added at 1 and 4 percent by weight of asphalt binder, recycled LLDPE at 7 percent, and HDPE at four dosages ranging from 1 to 3.5 percent. The PE-asphalt emulsions were prepared by using a high-shear mixer to blend PE (in pellet form) into asphalt binder at a temperature of 100 to 150°C. To obtain storage-stable PE-asphalt emulsions, four commercial copolymers and homopolymers were first studied for their stabilizing potential but found unsuccessful due to a lack of solubility in asphalt binder. Then, attempts were made to determine the feasibility of using specific enthalpic interactions, such as hydrogen bonding and charge transfer interactions, to improve the solubility of PE in asphalt and storage stability of PE-asphalt emulsions. It was found that because the two asphalt binders used in the study had very low phenol content, hydrogen bonding could not be formed. The charge transfer interactions were studied by proton nuclear magnetic resonance (NMR) spectroscopy, where spectra were collected of an equal-weight mixture of ethyl 3,5-dinitrobenzoate and the asphaltene fraction of an asphalt binder that was dissolved in deuterated o-xylene and chlorobenzene. The spectroscopy results showed that the charge transfer interactions between the asphaltene donor and the ethyl 3,5-dinitrobenzoate acceptor were maintained up to approximately 200°C, indicating that the energetic interactions could be used in the design of a soluble PE polymer. However, the chemical inactivity of these charge-accepting polymers made it of limited value for large scale paving applications. Finally, an in-situ stabilization of PE-asphalt emulsions was proposed. From the Fourier-transform infrared spectroscopy (FTIR) and gel permeation chromatography (GPC) analysis, the use of sulfur-assisted grafting reaction of asphalt onto a low molecular weight polybutadiene polymer was able to produce miscible PE-asphalt emulsion systems. The in-situ stabilized emulsions demonstrated long term storage stability at elevated temperatures, with particle size and particle size distributions controlled below 5 µm (Figure 4).

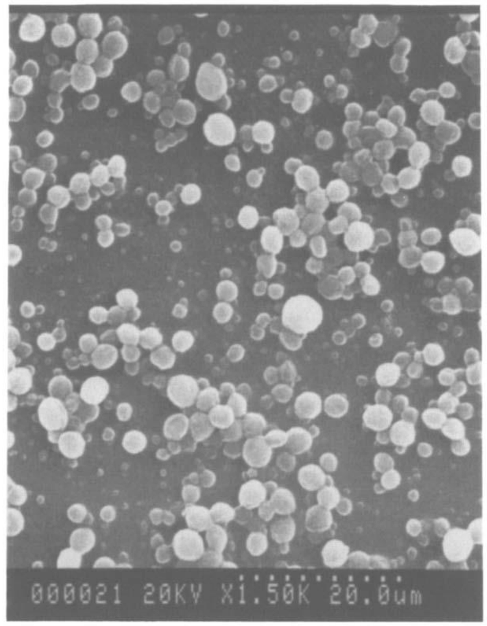


Figure 4. Scanning Electron Microscopy (SEM) Image of In-Situ Sterically Stabilized Polyethylene-Asphalt Emulsion (Liang and Hesp, 1993)

"Preparation and Characterization of Asphalt-Modified Polyethylene Blends" by W.H. Daly, Z. Qui, and I. Negulescu in Transportation Research Record, 1993.

Authors	W.H. Daly, Z. Qui, and I. Negulescu
Sponsor	Louisiana Transportation Research Center
Plastic Type	High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	5 to 20 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study characterized the compatibility, morphology, and rheological properties of asphalt binders modified with polyethylene (PE) via the wet process. Eight asphalt binders with viscosity grades ranging from AC-10 to AC-30 were tested. Three different types of PE were evaluated for asphalt modification: high-density polyethylene (HDPE), chlorinated HDPE (CPE), and maleated low-density polyethylene (MPE). CPE was prepared based on solution chlorination performed in 1,1,2,2,-tetrachloroethane (TCE), where 2,2-azobis(2-methylpropionitrile) (AIBN) was added to initiate the reaction with HDPE. The resultant CPEs had a weight percent of chloride varying from 2.7 to 15.2 percent. For the preparation of MPE, LDPE and a mixture of maleic anhydride (MEH) and triethyl phosphate (TEPA) were first dissolved in dichlorobenzene (DCB). Then, dicumyl peroxide (DCP) solution was added in the DCB to initiate the maleation process. The resultant MEH content of the CPE was controlled at 2.8 weight percent. For asphalt modification, HPPE and CPE was blended into the asphalt binder for 2 hours at 150°C under nitrogen, while MPE was mixed with the asphalt binder for 4 hours at 180°C under nitrogen. The dosage of PE used varied from 5 to 20 percent by weight of asphalt binder. Compatibility analysis by Differential Scanning Calorimetry (DSC) identified multiple transitions in the thermogram of AC-10 binders with and without HDPE and CPE at various weight ratios. These results indicated that high concentrations of HDPE and CPE disrupted the compatibility of asphalt binders. Fluorescence microscopy images showed enhanced compatibility of CPE over HDPE with an AC-10 binder, which was attributed to changes in the polymer polarity and morphology as a result of reduced crystallinity. Figure 5 presents the microscopy images of AC-10 binders modified with 10 percent HDPE and 10 percent CPE. The addition of PE for asphalt modification improved the low-temperature properties of asphalt binders based on the cracking temperature (T_c) results measured in the Dynamic Mechanical Analyzer (DMA) under a bending mode. Finally, asphalt binders modified with low-level CPE and MPE exhibited better rheological properties than those modified with HDPE in the dynamic rheology and creep and recovery tests. These results indicated that low-level chlorination or maleation was a potential approach to improving the compatibility of PE with asphalt binder.

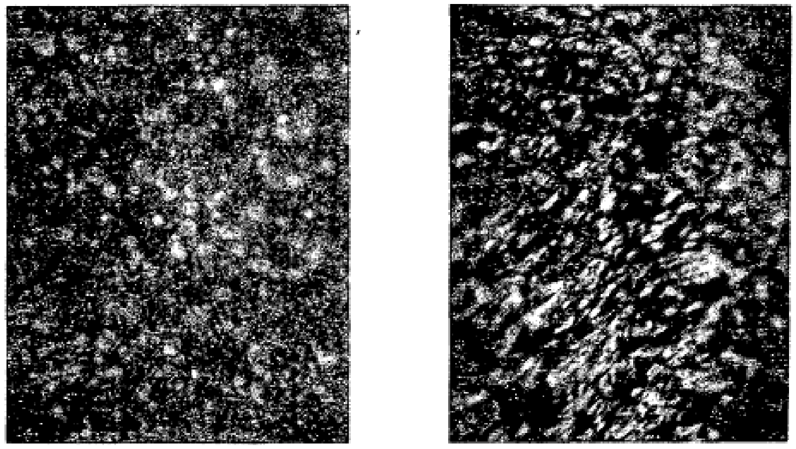


Figure 5. Fluorescence Microscopy Images of AC-10 Binders Modified with 10 Percent HDPE (left) and CPE (right) (Daly et al., 1993)

“Recycled Plastic Finds Home in Asphalt Binder” by L. Flynn in Roads & Bridges, 1993.

Authors	L. Flynn
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	5 to 6 Percent by Weight of Asphalt Binder
Scope	Field Project

This article investigated the suitability of using recycled polyethylene from grocery bags to reduce rutting and cracking of asphalt pavements, expressing that after the binder modification with these additives the extended pavement life remains uncertain. The article defines recycled plastic as plastics composed of post-consumer material (generated by a business or consumer) or recovered material (industrial scrap) only, or both, that may or may not have been subjected to additional steps of the type used to make products such as recycled regrind or reprocessed or re-constituted plastics. Regarding the performance and durability of recycled plastics as asphalt binder modifiers, the author indicated that while the performance of recycled polyethylene modifiers appeared to be holding up well in general, the oldest pavements in the U.S. that contained these modifiers did not last very long. Regarding cost-effectiveness, the author highlighted that the use of recycled polyethylene increased the cost of asphalt mix by 18 to 25 percent. In this synthesis, the highlighted prospective benefits of recycled polyethylene modifiers included: reduced permanent deformation in the form of rutting and shoving, especially in elevated pavement temperatures (80°F to 160°F); reduced fatigue and low temperature cracking; increased load-bearing capacity of the pavement at low temperatures; increased pavement resiliency and durability; reduced stripping and raveling due to enhanced binder cohesion to the aggregate; reduced binder oxidation and aging of the pavement; extended pavement life from 50 to 100 percent in some cases; and reduced maintenance. One interesting perspective highlighted by the author is that section 1038 of the Intermodal Surface Transportation Efficiency Act (ISTEA) called for the U.S. DOT, in cooperation with the states, to conduct studies to determine the feasibility of using recycled plastics as well as other recycled materials. In addition, if found feasible, recycled plastic can be substituted for up to 5 percent of recycled rubber that is mandated for use in asphalt pavements as a percentage of the total tons of asphalt laid in a state on federally funded projects. It was estimated that if 5 percent of recycled plastic was incorporated in all asphalt mixtures in the U.S., between 2.3 to 2.5 billion lb. of recycled plastic per year could be reused. The author indicated two patented process that used recycled polyethylene in the production of modified asphalt binders: Novophalt® and Polyphalt®. In terms of price, both the Novophalt® and Polyphalt® products were listed as competitive with virgin polymer modifiers. Typically, the Novophalt® polyethylene modifier could compose 5 to 6 percent by weight of asphalt binder. In general, the cost of the Novophalt® modifier added about $7 per ton to the cost of asphalt mix. The author indicated that the first placement of an asphalt pavement using the Novophalt® binder took place in October 1986 in Sherman, Texas. A viscosity grade AC-10 asphalt cement composed the base binder. Nearly seven years later, the pavement was reported to be in good condition. In one of the more notable applications involving the

Novophalt® binder, 22,000 tons of the product were used in the reconstruction of Runway 17-35 at the William P. Hobby Airport in Houston in October 1988 and January 1989. The project, which was placed over a PCC base, was 7 in. thick at the center and 3.2 in. at the edge. The binder content ranged from 4.8 to 5.0 percent. Four years after placement there were no signs of rutting, fatigue or reflective cracking. Regarding Polyphalt®, the author indicated that the first test section using the modifier was performed in Toronto in October 1992 (Figure 6). The project placed 150 to 200 tons of asphalt containing about 10,000 gal of Polyphalt® asphalt binder.

Figure 6. Polyphalt® Test Section in Toronto in October 1992 (Flynn, 1993)

"The Development and Performance of an Environmentally Responsible Modified Binder" by B. Harbinson and A. Remtulla in the *Proceedings of the 9th AAPA International Asphalt Conference, Surfers Paradise, Australia*, 1994.

Authors	B. Harbinson (Polyphalt Inc., Canada) and A. Remtulla (SAMI Pty Limited, Australia)
Sponsor	Unknown
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Polyphalt®)
Plastic Dosage	Not Specified
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This paper discusses the development and performance of an environmentally responsible modified binder technology – Polyphalt®. The Polyphalt® technology produces storage-stable asphalt binders modified with virgin or recycled polyethylene. Most field projects constructed to date used low-density polyethylene (LDPE) for Polyphalt® modification, but laboratory data indicated that other types of recycled plastics such as linear low-density polyethylene (LLDPE) and high-density polyethylene (HDPE) could also be used. Table 2 summarizes the traditional physical properties of Polyphalt® L and M binders. From the rheological data, Polyphalt® binders showed significantly better high-temperature and low-temperature performance properties than unmodified binders. Furthermore, Polyphalt® binders were less susceptible to oxidative aging due to polyethylene modification. No phase separation was observed in Polyphalt® binders after being stored up to 28 days at 135°C. However, details about the formulations of Polyphalt® binders were not provided. Mixture performance testing was also conducted on a typical structural mix in Australia using different asphalt binders: one unmodified binder, one styrene-butadiene-styrene (SBS) modified binder, one crumb rubber modified binder, and three Polyphalt® binders. All modified mixtures had significantly lower creep rates than the unmodified control mixture in the dynamic creep test, indicating better resistance to permanent deformation. The workability evaluation using a gyratory compactor indicated that asphalt mixtures containing Polyphalt® binders were more workable and required about 25 percent fewer compaction cycles than those containing other binders. Field trials had been successfully constructed in Canada and Australia using Polyphalt® binders. No difference in the handling, construction, and fume/odor emissions was reported between conventional and Polyphalt® mixtures.

Table 2. Physical Properties of Polyphalt® L and M Binders (Harbinson and Remtulla, 1994)

Test	Unit	AUSTROAD AB-2 Specification	5% P101	Polyphalt L	AUSTROAD AB-3 Specification	5% P503	Polyphalt M
Penetration @25C	p.u	40 min	58	58	45 min	50	82
Torsional Recovery @25C	%	8 min	9	7	18 min	19	40
Softening Point	DegC	60 min	62.5	56.5	62 min	65	68.5
Viscosity @135C	Pa.s	1.0 min	0.5	1.2	2.2 max	1.4	2.0
Elastic Recovery @60C	%	50 min	31	21	45 min	61	94
Viscosity by Elastomer @60C	Pa.s	2200 min	1485	419	1800 min	1485	4345

“Properties and New Developments of High Modulus Asphalt Concrete” by J.P. Serfass, P. Bense, and P. Pellevoisin in the *Proceedings of the International Conference for Asphalt Pavements*, 1997.

Authors	J.P. Serfass, P. Bense (SCREG Routes, France), and P. Pellevoisin (Recherche-Technique-Entreprise, France)
Sponsor	Unknown
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Dry Process
Plastic Dosage	Not Specified
Scope	Laboratory Mixture Testing, Field Project

This study developed a new type of high-modulus (HM) asphalt mix with superior stiffness, rutting resistance, and fatigue resistance. The new HM mix was designed with an extremely high asphalt binder content of 6.4 to 8.0 percent. The mix had a richness factor between 4.0 and 5.0, which was calculated as a function of the asphalt binder content, effective specific gravity and surface area of the combined aggregates. The asphalt binder used had a 10/20 penetration grade and was further modified with polyethylene (PE) via the dry process. The dosage of PE used was not provided. Laboratory test results indicated that the new PE modified HM mix had significantly better resistant to rutting, fatigue cracking, and moisture damage than the standard base mix. The study also discussed the first large-scale field project of PE modified HM asphalt mix. The project was an overlay of a motorway, which had historically severe rutting issues due to extremely heavy traffic, long ramps with a steep gradient, and a hot climate. The project was placed in April to May 1994. After two and a half years in-service, it performed extremely well with no rutting. Following the success of this project, several field projects were constructed using the PE modified HM asphalt mix and had all been performing well.

“Polyethylene Modified Binders in the Chirivel Section (Almeria) – Province Limit with Murica A-92 North” by A. Cernuda, A. Recio, R. López, and J. García in *Proceedings of First Andalusian Road Congress Seminar*, 1998.

Authors	A. Cernuda A., A. Recio A., R. López, R. and J. García (affiliation not identified)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene
Plastic Addition Method	Wet Process
Plastic Dosage	5% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

In the project "Chirivel (Almería) - Limit of the province with Murcia" of A-92 north, the specifications required the use of recycled polyethylene (PE) for asphalt mixture production. In this region, many plastic greenhouse roofs made of polyethylene are used, making the situation ideal for using this product as a polymer for modifying the asphalt binder via the wet process. The modified binder was produced at the asphalt plant using a high-shear blender, where 5% recycled PE (by weight of asphalt binder) was blended into an 80/100 penetration grade binder at 195°C (383°F). The modified binder was then kept in an agitated storage tank until used for mixture production. Due to the increase in binder viscosity from PE modification, the mixing and compaction temperature of the modified mixture was recommended to increase by 5 to 10°C. Conventional binder characterization tests were carried out, and the dispersion of PE in asphalt binder was also analyzed using a fluorescence microscope (FM).

After carrying out tests on correctly and incorrectly dispersed binder samples, it was concluded that the quality of PE modified binders was directly dependent on the degree of PE dispersion. Regarding asphalt mixture characterization, this study compared the properties of the PE modified mixture versus a control mixture containing a 60/70 penetration grade binder. The Marshall stability and wheel tracking test results indicated that overall, the PE modified mixture had higher stability and better rutting resistance than the control mixture at different binder contents. The indirect tensile strength (ITS) test was conducted on 4-inch field extracted samples, of which the results showed that the PE modified mixture exhibited adequate adhesiveness as evidenced by a tensile strength ratio (TSR) between 80 to 100% while the specification requirement is a minimum TSR of 75%. Finally, the authors recommended strictly monitoring the production of PE modified binders to guarantee the continuity of the required binder properties. Due to the low storage stability of PE modified binders, the authors also recommended minimizing the time between binder production and mixture production at the plant, which can be solved by using a mobile modified binder manufacturing facility.

“Al Kharkheer Airport Project Design and Evaluation of Novophalt Modified Binder and Asphalt Mix” by General Directorate of Military Works, Kingdom of Saudi Arabia, 1999.

Authors	General Directorate of Military Works (Saudi Arabia)
Sponsor	Unknown
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	5.5 Percent by Weight of Asphalt Binder
Scope	Field Project, Laboratory Mixture Testing

This report discusses the design and evaluation of Novophalt® modified asphalt binder and wearing course for the construction of Al Kharkheer Airport in Saudi Arabia. The project was a collaboration among the General Directorate of Military Works, Presidency of Civil Aviation of the Kingdom of Saudi Arabia, and Netherlands Airport Consultants. The Novophalt® binder was formulated by modifying a locally supplied 60/70 penetration grade binder with 5.5 percent low-density polyethylene (LDPE) by weight of asphalt binder, using a patented high-shear blending unit at the asphalt plant (Figure 7). The Novophalt® binder met the Superpave PG 76-16 requirements while the base binder was graded as PG 64-16. The Novophalt® mixture was designed using the Marshall mix design procedure, which resulted in an optimum binder content of 5.0 percent. After mix design, the Novophalt® mixture was tested in a variety of mechanistic performance tests. Marshall stability and flow, indirect tensile strength, and resilient modulus results were all within the specification limits. The loss in Marshall stability due to moisture conditioning was less than 10 percent, indicating superior resistance to moisture damage. The Novophalt® mixture had a low permanent strain value and a small steady-state creep slope in the dynamic creep test, which indicated good resistance to permanent deformation at high in-service pavement temperatures. Finally, fuel resistance testing was conducted, and the results complied with agency specifications. Construction of the project commenced in October 1998 and finished in March 2000. Figure 8 shows several photos taken from the construction of the project.

Figure 7. Formulation of Novophalt® Binder at the Asphalt Plant (General Directorate of Military Works, 1999)

Figure 8. Photos of Construction of Al Kharkheer Airport in Saudi Arabia (General Directorate of Military Works, 1999)

“Recycled Plastic Fibers for Asphalt Mixtures” by M. Lalib and A. Maher in *Federal Highway Administration Report FHWA 2000-04*, 1999.

Authors	M. Lalib and A. Maher (New Jersey Department of Transportation)
Sponsor	Federal Highway Administration
Plastic Type	Recycled Polypropylene (PP)
Plastic Addition Method	Dry Process
Plastic Dosage	5, 10, and 15 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the applicability of using recycled plastic fibers shredded from fishing nets to improve the mechanical properties and performance of asphalt mixtures. Two types of fibers were obtained from the New Jersey Marine Science Consortium in Fort Hancock, New Jersey: a monofilament gill net made of nylon, and a trawl net made of polypropylene (PP). The binder used in the preparation of test specimens was AC-20 asphalt cement. The binder content was kept constant at 7 percent by weight of total aggregate. Three dosages of fibers for each of the two types of nets were incorporated via the dry process. The nylon trawl net was tested at 2.5, 5, and 10 percent by weight of asphalt binder, while the PP gill net was tested at 5, 10, and 15 percent by weight of asphalt binder. Test results indicated that both the air voids and voids in mineral aggregate (VMA) increased with increasing the fiber dosage for both the nylon and PP fibers. Overall, all mixtures had very low flow values in the Marshall stability test. Adding the smallest amount of nylon fiber improved the mixture’s Marshall stability. For the PP fibers, the stability increased above the control value with increasing the fiber dosage. Also, a problem with fiber clumping was encountered when using nylon fibers, but not with PP fibers. Finally, the authors concluded that in many cases, the addition of fishing net waste fibers improved the performance properties of asphalt mixtures.

"Reuse of Crumb Rubber and Plastic on Hot-Mixed Asphalt Concrete" by A. Tuncan, M. Tuncan, and A. Cetin in 2nd *Eurasphalt & Eurobitume Congress*, 2000.

Authors	A. Tuncan, M. Tuncan, and A. Cetin (Anadolu University, Turkey)
Sponsor	Unknown
Plastic Type	Low-density polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	5, 10 and 20 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study investigated the effects of crumb rubber and plastics on asphalt pavements. Limestone aggregate and a 75/100 penetration grade binder were tested. The crumb rubber was obtained from scrap automobile tires and had particle sizes varying between the #4 and #200 sieves. The plastic was obtained from grocery bags and pallet wrap and had particle sizes varying between the #4 and #10 sieves. The primary polymer makeup of the plastic sample was low-density polyethylene (LDPE). Both crumb rubber and plastic were added at dosages of 5, 10, and 20 percent by weight of asphalt binder. From the Marshall test, it was found that the addition of rubber decreased the Marshall stability when the rubber dosage exceeded 10 percent, while the addition of plastic increased the Marshall stability due to enhanced binding of the modified binder with the aggregates. The study also observed that the dosage of rubber and plastic had an impact on the indirect tensile strength of asphalt mixtures. The indirect tensile strength of rubber modified mixtures increased as the dosage of rubber between #4 and #20 sieves increased. A similar trend was also observed for plastic modified mixtures. When the asphalt binder was modified with 20 percent plastic, a 69 percent increase in the indirect tensile strength was observed.

“Composite Asphalt Binders: Effect of Modified RPE on Asphalt” by A.A. Yousefi, A. Ait-Kadi, and C. Roy in *Journal of Materials in Civil Engineering*, 2000

Authors	A.A. Yousefi, A. Ait-Kadi, and C. Roy (Laval University, Canada)
Sponsor	Natural Sciences and Engineering Research Council of Canada and the Fonds pour la formation de chercheurs at l’aide a` la recherche of Quebec
Plastic Type	Recycled Polyethylene
Plastic Addition Method	Wet Process
Plastic Dosage	1% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of recycled polyethylene (RPE) and different copolymers for asphalt binder modification via the wet process. The type of RPE used was high-density polyethylene. Two different copolymers were used to modify the RPE at a dosage of 7.0% by weight of RPE. The unmodified and modified RPE was added into a 150/200 penetration grade binder for modification at a dosage of 1.0% by weight of asphalt binder. Blending was conducted at 160°C for three hours at varying speeds. Asphalt binders with and without RPE modification were then tested for rheological, morphological, thermal, and storage stability characterization using a variety of laboratory binder tests.

The dynamic shear rheometer (DSR) stress sweep test indicated that RPE modification significantly affected the rheological properties of the asphalt binder and that the test results did not fit well with the rheological models developed for polymers. Furthermore, the DSR stress sweep test, along with the penetration, softening point, and creep-recovery tests, indicated that adding RPE stiffened the asphalt binder with increased softening point as well as reduced penetration and creep compliance. This stiffening impact, however, was found to vary for unmodified versus modified RPE. The RPE modified binders exhibited a special morphology mainly due to the swelling of RPE particles and their interactions with asphaltenes. The storage stability test based on softening point testing did not identify the phase separation issue of RPE modified binders. However, a different trend was observed from the modified storage stability test based on DSR testing and optical microscopy. These results indicated that the modified storage stability test was more effective in evaluating the phase separation of polymer modified binders than the conditional test procedure based on softening point testing. The study concluded that the asphalt-RPE system did not need compatibilization but stabilization because of the phase separation issue.

"Validation of Asphalt Binder and Mixture Tests that Measure Rutting Susceptibility" by K.D. Stuart, W.S. Mogawer, and P. Romero as *Federal Highway Administration Report FHWA-RD-99-204*, 2000.

Authors	K.D. Stuart, W.S. Mogawer, and P. Romero (Federal Highway Administration)
Sponsor	Federal Highway Administration
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	6.5 Percent by Weight of Asphalt Binder
Scope	Accelerated Pavement testing, Laboratory Mixture Testing

This report discusses a research study conducted by the Federal Highway Administration (FHWA) to validate Superpave asphalt binder and mixture tests for the evaluation of rutting susceptibility of asphalt mixtures. Twelve full-scale pavement sections were constructed at the FHWA's Accelerated Loading Facility (ALF); seven of them were used for a rutting study while the other five were used for a fatigue cracking study. Five different asphalt binders were included: AC-5, AC-10, AC-20, Novophalt® binder, and Styrelf I-D binder with Superpave performance grades of 58-34, 58-28, 64-22, 76-22, and 82-22, respectively. The Novophalt® binder was formulated by modifying an AC-10 binder with 6.5 percent low-density polyethylene (by weight of asphalt binder) using a patented high-shear mill at an asphalt plant in Virginia. The Styrelf I-D binder was formulated by modifying an AC-20 binder with 4 percent styrene-butadiene (by volume of asphalt binder). All 19.0 mm nominal maximum aggregate size surface mixtures were designed using the Marshall mix design procedure with a compactive effort of 75 Marshall blows, resulting in optimum binder contents ranging from 4.7 to 4.9 percent. Each mixture was placed as an 8-inch surface layer (constructed in four 2-inch lifts) on top of 18-inch unbound crushed aggregate base and an A-4 subgrade per AASHTO M 145-91 classification.

The experimental design of the ALF rutting study required testing each pavement section at three pavement temperatures ranging from 46 to 76°C. However, because of the difference in the high-temperature properties of the five binders tested, the only temperature used for all rutting pavement sections was 58°C. Figure 9 presents the measured rut depth in the asphalt pavement layer after up to 10,000 ALF wheel passes. As shown, pavement sections using the Novophalt® and Styrelf I-D binders significantly outperformed those using unmodified binders in terms of rutting resistance. These results highlighted the enhanced high-temperature performance properties of asphalt binders due to polymer modification.

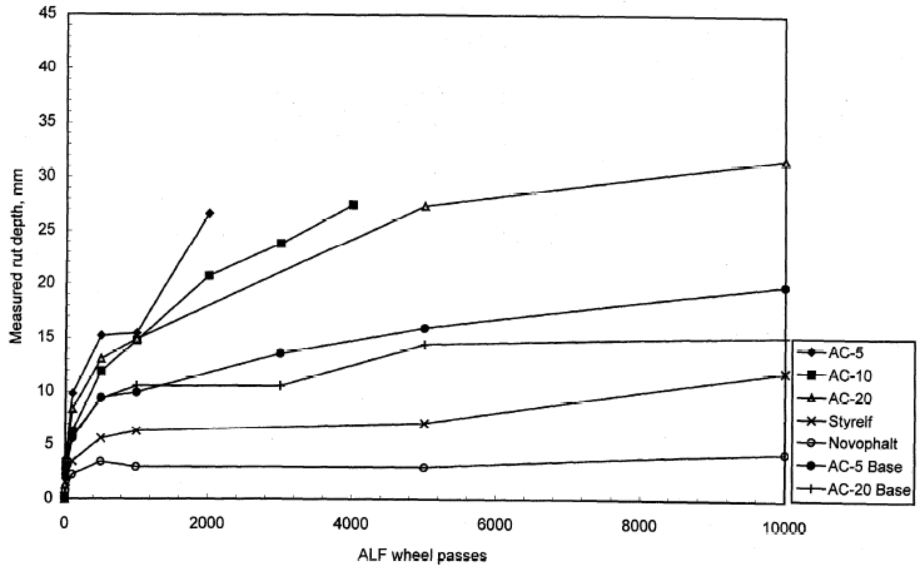


Figure 9. Field Rut Depth in the Asphalt Pavement Layers (Stuart et al., 2000)

During construction of the ALF pavement sections, virgin binders and plant mixes were sampled and tested in a wide variety of laboratory rutting tests. The primary asphalt binder test used was the Superpave rutting parameter, G*/sin(δ). Asphalt mixture tests evaluated in the study included Marshall stability and flow, gyratory testing machine, French pavement rutting tester (PRT), Georgia loaded-wheel tester (LWT), Hamburg wheel-tracking device (WTD), asphalt-aggregate mixture analysis system, repeated load compression test, and Superpave shear tester. Test results were analyzed to determine their correlation to field rut depth on ALF. It was found that the G*/sin(δ) rutting parameter could discriminate the rutting resistance of unmodified binders but not polymer modified binders. The Novophalt® binder had a lower G*/sin(δ) value, than the Styrelf I-D binder, which indicated reduced rutting resistance; however, the field rut depth data of these two pavement sections showed the opposite trend. Among the different mixture rutting tests, the French PRT, Georgia LWT, and Hamburg WTD results ranked the five surface mixtures the same as the field rut depth data on ALF, where the Novophalt® mixture showed the best rutting resistance, followed by the Styrelf I-D mixture, and then the three unmodified mixtures, respectively. Table 3 summarizes the French PRT, Georgia LWT, and Hamburg WTD results.

Table 3. French PRT, Georgia LWT, and Hamburg WTD Test Results (Stuart et al., 2000)

Rutting Tests	Test Parameter	AC-5	AC-10	AC-20	Novophalt®	Styrelf I-D
French PRT (60°C, 0.875 rad/s, 30,000 cycles)	Rut Depth (%)	15.5	13.8	6.4	2.6	3.7
Georgia LWT (40°C, 0.13 rad/s, 8,000 cycles)	Rut Depth (mm)	7.4	5.4	3.7	1.4	1.9
Hamburg WTD (50°C, 0.13 rad/s, 20,000 cycles)	Rut Depth (mm)	> 30	> 30	8.5	1.9	2.8
	Creep Slope (Passes/1mm)	300	630	6,220	24,600	17,900

"Improved Storage Stability of LDPE/SBS Blends Modified Asphalts" by G. Gao, Y. Zhang, Y. Zhang, K. Sun, and Y. Fan in *Polymers & Polymer Composites*, 2002.

Authors	G. Gao, Y. Zhang, Y. Zhang, K. Sun, and Y. Fan (Shanghai Jiao Tong University, China)
Sponsor	National Science Foundation of China
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	0.5 to 1.5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study introduced an approach to obtain storage-stable asphalt binders modified with low-density polyethylene (LDPE) and styrene-butadiene-styrene (SBS). LDPE was obtained from a commercial source with a melt flow rate of 2.0g/10 min. The base binder used for LDPE/SBS modification had a penetration of 90 dmm, softening point of 47.5°C and viscosity of 0.35 Pa.s at 135°C. For the preparation of LDPE/SBS modified binders, a high-shear mixer (4,000 rpm) was used to blend the LDPE and SBS into asphalt binder for 1 hour at 180°C. Then, element sulfur was added into the asphalt binder and high-shear mixing continued for 1 hour. In cases where the preblended LDPE/SBS copolymer was used, the two individual polymer components were copolymerized in the mixing chamber of a rheometer at 80 rpm and different mixing temperatures ranging from 115°C to 150°C. The LDPE/SBS copolymer (in 1:2 ratio) was added at three dosages: 1.5, 3.0, and 4.5 percent by weight of asphalt binder, while sulfur was added at 0.05, 0.1, and 0.15 percent by weight of asphalt binder. The Haake curves of mixing LDPE/SBS blends showed possible crosslinking or grafting between LDPE and SBS, where the viscosity and mixing torque decreased as the polymer molecules degraded under high shear stress. The mixing temperature had an impact on the time of initiation of the crosslinking reaction. From the cigar-tube storage stability test, it was found that asphalt binders modified by adding LDPE and SBS directly in the absence of sulfur were subject to phase separation. Adding sulfur reduced the difference in the softening points between the top and bottom cigar-tube portions, but the difference in viscosity was still significant. Polymer separation became more severe as the LDPE dosage increased. On the other hand, asphalt binders modified with the preblended LDPE/SBS copolymer had significantly better storage stability in the presence of sulfur. No coalescence of LDPE and SBS particles was observed after storage for 48 hours at 163°C. The improved storage stability was also confirmed in the optical micrographs where the asphalt binders modified with preblended LDPE/SBS copolymer showed better morphology than those modified with LDPE and SBS added directly. Finally, adding LDPE and SBS improved the rheological properties, especially the high-temperature rutting resistance, of asphalt binders measured in the dynamic shear rheometer (DSR) temperature sweep test. Table 4 presents the DSR *G*/sin(δ)* results, where asphalt binders modified with LDPE and SBS had consistently higher high-temperature PG than the unmodified binder.

Table 4. Superpave High-Temperature Performance Grades (Gao et al., 2002)

	Temperature (°C) at $G^*/\sin\delta$= 1kPa
Asphalt (AH-90)	68.4
Asphalt/1% LDPE /2% SBS	74.1
Asphalt/1% LDPE /2% SBS /0.1% sulfur	84.1
Asphalt/3% LDPE/SBS (34:66) blend/0.1% sulfur	82.9

“NOVOPHALT Polymer Modified Asphalt Design for Casement Aerodrome at BALDONNEL” by ROADSTONE Dublin Ltd., 2002.

Authors	ROADSTONE Dublin Ltd. (Ireland)
Sponsor	Unknown
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	5.0 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This report documents the mix design results of a Novophalt® polymer modified mixture for Casement Aerodrome (a military airbase) in Dublin, Ireland. The Novophalt® binder was formulated by modifying a 70/100 penetration grade binder with recycled low-density polyethylene (LDPE) using a patented high-shear blending unit at the asphalt plant. The dosage of recycled LDPE used for Novophalt® modification was 5.0 percent by weight of asphalt binder. The Novophalt® binder met the PG 76-22 requirements, while the base binder was graded as PG 64-22. The Novophalt® mixture was designed using the Marshall mix design procedure, which resulted in an optimum binder content of 5.4 percent. At the optimum binder content, the Novophalt® mixture had an average dry indirect tensile (IDT) strength of 1.74 MPa, an average wet IDT strength of 1.68 MPa, and a resulting tensile strength ratio of 96.3 percent. The loss of Marshall stability due to 24-hour immersion in water was less than 10 percent. The mixture had an average resilient modulus value of 13,696.5 MPa and 5,500 MPa at 0°C and 25°C, respectively. The permanent strain in the dynamic creep test was less than 0.8 percent. The average loss after 24-hour immersion in jet fuel was 1.6 percent. Based on these results, the Novophalt® mix design was approved. A trial section was scheduled to be placed on September 2, 2002.

“Utilization of Waste Plastics in Asphalt Mixtures” by O. Kamada and M. Yamada in *Memoirs of the Faculty of Engineering, Osaka City University*, 2002.

Authors	O. Kamada and M. Yamada (Osaka City University, Japan)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE), Recycled Polypropylene (PP)
Plastic Addition Method	Dry Process
Plastic Dosage	Up to 10 Percent by Volume of Asphalt Mixture
Scope	Laboratory Mixture Testing

This study evaluated the use of recycled polyethylene (PE) and polypropylene (PP) for asphalt mixture modification via the dry process. Two asphalt mixtures were tested: a dense-graded mixture and an open-graded mixture. Each mixture was modified by adding up to 10 percent recycled plastics (by volume of asphalt mixture) as aggregate replacement. A sweep of mixture performance tests was conducted, including the wheel tracking test, immersion wheel tracking test, bending fatigue test (for dense-graded mixtures only), and oil-resistant test (for open-graded mixtures only). Test results indicated that adding PE improved the rutting, fatigue, and stripping resistance of the dense-graded mixture; however, the improvement varied among different types of recycled PE used. The PP modified dense-graded mixture, on the other hand, showed better rutting resistance than the unmodified mixture but had no improvement in terms of fatigue and stripping resistance. Finally, the addition of PE improved the resistance of open-graded mixtures to rutting, stripping, and gasoline immersion, as indicated by increased dynamic stability in the wheel tracking test, extended failure time in the immersion wheel tracking test, and increased retained stability in the oil-resistant test, respectively.

“Rubber-polyethylene Modified Bitumens” by A.A. Yousefi in *Iranian Polymer Journal*, 2003.

Authors	A.A. Yousefi (Iran Polymer and Petrochemical Institute, Iran)
Sponsor	IPI Research Council
Plastic Type	High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	1 and 3 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the impact of different polyethylene and rubber blends on the performance properties of asphalt binders. Two grades of low-density polyethylene (LDPE), one grade of linear low-density polyethylene (LLDPE), and six grades of high-density polyethylene (HDPE) from a commercial source were used, along with two synthetic rubbers [polybutadiene rubber (PBR) and styrene-butadiene-styrene random copolymer (SBR)], a natural rubber, and two styrene-ethylene-butylene-styrene tri-block copolymers (SEBS). The base binder used for polyethylene and rubber modifications had a 40-penetration grade. To prepare the modified binders, a high-shear mixer was used to blend the polyethylene and rubber into asphalt binder for 30 minutes at 170 to 180°C. All polyethylene and rubber additives except LLDPE were added at 3 percent by weight of asphalt binder, while the dosage of LLDPE used was 1 percent by weight of asphalt binder. The modified binders were subject to morphological analysis, penetration test, softening point test, Frass breaking point test, and performance grading. Test results indicated that only the PBR-PE blends formed a physical network in the asphalt binder, whereas their SBR, NR and SEBS counterparts did not. Nevertheless, asphalt binders modified with SBR-PE blends exhibited the best elastic recovery and film-forming properties. As compared to LDPE and HDPE, LLDPE was found more effective in changing the performance properties of asphalt binders. The addition of heavy vacuum slopes (HVS) oil significantly improved the low-temperature properties of asphalt binders modified with LDPE and HDPE. The dosage of HVS oil could be adjusted accordingly to meet the performance grade requirements of LDPE and HDPE modified binders. Finally, adding HVS oil into the ternary rubber-PE-asphalt blends increased the volume of rubber particles.

“Use of Waste High Density Polyethylene as Bitumen Modifier in Asphalt Concrete Mix” by S. Hinislioglu and E. Agar in *Materials Letters*, 2004.

Authors	S. Hinislioglu (Ataturk University, Turkey) and E. Agar (Istanbul Technical University, Turkey)
Sponsor	Ataturk University Research Fund
Plastic Type	Recycled High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	4, 6, and 8 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the use of recycled high-density polyethylene (HDPE) for asphalt modification via the wet process. The base binder used had an AC-20 grade. The HDPE sample was tested in powder form with 100 percent passing the No. 10 sieve but retained on the No. 40 sieve. A low-shear mixer (200 rpm) was used to prepare HDPE modified binders at various mixing temperatures (145, 155, and 165°C) and mixing times (5, 10, 15, and 30 minutes). HDPE was added at three dosages: 4, 6, and 8 percent by weight of asphalt binder. After modification, the HDPE modified binders were mixed with aggregates, short-term conditioned, and compacted. Each HDPE modified mixture was tested using the Marshall stability test. It was found that the Marshall stability values decreased as the HDPE dosage increased for all combinations of mixing temperature and mixing time. The 4 percent HDPE modified mixtures had consistently higher Marshall stability values than the unmodified control mix. Among all the mixtures tested, the 4 percent HDPE mixture prepared at a mixing temperature of 165°C and mixing time of 30 min had the highest Marshall stability value. The Marshall flow results showed an opposite trend as the Marshall stability results, where higher Marshall flow values were observed for modified mixtures containing higher HDPE dosages. All modified mixtures except the one prepared using 4 percent HDPE, a mixing temperature of 165°C, and mixing time of 30 minutes had higher Marshall flow values than the unmodified control mix. Finally, the Marshall Quotient parameter was used to determine the impact of HDPE modification on the rutting resistance of asphalt mixtures. The 4 percent HDPE modified mixture prepared using a mixing temperature of 165°C and mixing time of 30 minutes had a Marshall Quotient value that was 50 percent higher than that of the unmodified control mixture, which indicated significant improvement in mixture rutting resistance due to HDPE modification.

"Asphalt Modification with Different Polyethylene-based Polymers" by G. Polacco, S. Berlincioni, D. Biondi, J. Stastna, and L. Zanzotto in *European Polymer Journal*, 2005.

Authors	G. Polacco, S. Berlincioni, D. Biondi (Universita` di Pisa, Italy), J. Stastna, and L. Zanzotto (University of Calgary, Canada)
Sponsor	Natural Sciences and Engineering Research Council of Canada, Husky Energy Inc.
Plastic Type	Polyethylene-based Polymers
Plastic Addition Method	Wet Process
Plastic Dosage	6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of different polyethylene (PE)-based polymers for asphalt modification via the wet process. The base binder used had a 70/100 penetration grade. Eight different PE-based polymers were tested, including two low-density polyethylene (LDPEs) with different molecular weights, a copolymer polyethylene-acrylic acid (PE-AA), two combinations of LDPE and ethylene-based reactive terpolymers [ethylene, butyl acrylate and glycidyl methacrylate (GMA)], two PE modified with GMA functional groups, and a linear low-density polyethylene (LLDPE). Each PE-based polymer was added at a dosage of 6.0 percent by weight of asphalt binder. For the preparation of polymer modified binders, the base binder was first heated for 2 hours at 180°C and then agitated using a high-shear mixer at 4,000 rpm. Then, the PE-based polymer was added into the binder and blended for 2 additional hours at 180°C. All modified binders were tested for softening point, storage stability, and fluorescence microscopy. Test results indicated that in all cases, PE-based polymer modified binders were subjective to phase separation and storage instability. The addition of ethylene-based reactive terpolymers and GMA functional groups improved the compatibility and miscibility between PE and asphalt binder; nevertheless, the improvement was insufficient to produce a homogenous and storage stable binder blend. Among all the PE-based polymers tested, LLDPE showed the greatest compatibility with asphalt binder. Further testing showed that the LLDPE modified binder had significantly different rheological and viscosity characteristics from the base binder, which indicated a possible formation of crosslinking between LLDPE and asphalt binder during high-shear mixing.

"Effects of High Density Polyethylene on the Permanent Deformation of Asphalt Concrete" by S. Hinislioglu, H.N. Aras, and O.U. Bayrak in *Indian Journal of Engineering & Material Sciences*, 2005.

Authors	S. Hinislioglu, H.N. Aras, and O.U. Bayrak (Ataturk University, Turkey)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	1 to 4 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the effect of high-density polyethylene (HDPE) on the permanent deformation of asphalt mixtures. HDPE was added into the asphalt binder for modification via the wet process. The HPDE sample was provided in powder form with 100 percent passing No. 10 sieve but retained on No. 40 sieve and had a specific gravity of 0.935. The base binder used was an AC-10 asphalt binder. For the preparation of HDPE modified binders, a high-shear mixer (3,000 rpm) was used to blend HDPE into the asphalt binder for 60 minutes at 185°C. The dosage of HDPE varied from 1 to 4 percent by weight of asphalt binder. Binder test results indicated that adding HDPE stiffened the asphalt binder, as indicated by increased softening point and decreased penetration and ductility. A dense-graded Marshall mix design with 5.0 percent asphalt binder content was used for the characterization of mixture volumetrics and performance properties. HDPE modified mixes had consistently lower densities than the control mix. HDPE modification did not have a significant impact on mixture volumetrics; HDPE modified mixes had similar air voids, voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) as the control mix. In the Marshall stability test, all HDPE modified mixes showed consistently higher Marshall stability and lower flow values than the control mix, indicating improved stability and resistance to permanent deformation. A similar trend was also observed in the creep test where HDPE modified mixes had lower creep strains, and thus, better rutting resistance, than the control mix. Finally, based on the Marshall stability and creep test results, 2 percent HDPE was selected as the optimum dosage for asphalt modification.

"Influence of M_w of LDPE and Vinyl Acetate Content of EVA on the Rheology of Polymer Modified Asphalt" by I.A. Hussein, M.H. Iqbal, and H.I. Al-Abdul Wahhab in *Rheologica Acta*, 2005.

Authors	I.A. Hussein, M.H. Iqbal, and H.I. Al-Abdul Wahhab (King Fahd University of Petroleum & Minerals, Saudi Arabia)
Sponsor	King Fahd University of Petroleum & Minerals, Saudi Arabia
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	4, 6 and 8 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

The main objective of this research was to evaluate the effect of asphalt binder modification with LDPE and ethyl-vinyl-acetate (EVA) polymers. Each polymer was added at three different dosages: 4, 6, and 8 percent by weight of asphalt binder. Two LDPE polymers with different molecular weight (M_w) and two EVA polymers with different vinyl-acetate content and molecular weight were tested. An asphalt binder with a 60/70 penetration grade and 30 percent asphaltenes was used for polymer modification. Results indicated that EVA polymers decreased the flow activation energy of asphalt binder, reducing its temperature sensitivity (i.e., change of viscosity). For LDPE, the activation energy increased with the increase of polymer dosage, suggesting that this polymer was more sensitive to temperature than EVA. Storage stability results were acceptable for binders modified with LDPE and EVA with low vinyl-acetate content. However, EVA with high vinyl-acetate content showed the highest degree of phase separation. Regarding aging susceptibility after RTFO, the modified binders were found to harden due to aging without any correlation to M_w or vinyl-acetate content observed. The high-temperature performance grade of asphalt binder increased after its modification with EVA with low vinyl-acetate content. It was concluded that the M_w of LDPE as well as the M_w and vinyl-acetate content of EVA polymers had an impact on the rheology, storage stability, and aging susceptibility of asphalt binders. Overall, EVA with low vinyl-acetate content was considered most suitable for asphalt modification in this study.

"Use of Plastic Waste (Poly-ethylene Terephthalate) in Asphalt Concrete Mixture as Aggregate Replacement" by A. Hassani, H. Ganjidoust, and A.A. Maghanaki in *Waste Management and Research*, 2005.

Authors	A. Hassani, H. Ganjidoust, and A.A. Maghanaki (Tarbiat Modarres University, Iran)
Sponsor	The Research Center of Road and Transportation Ministry of Iran
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	5 to 15 Percent by Weight of Asphalt Mixture
Scope	Laboratory Mixture Testing

This study investigated the use of PET in asphalt mixtures as aggregate replacement (Plastiphalt) to reduce the environmental effects of PET disposal. The PET sample was provided in granule pellet form with about 3 mm diameter (Figure 10). It was added into asphalt mixture by replacing 20 to 60 percent (by volume) of aggregates with a size between 2.36 mm and 4.75 mm. These replacement percentages corresponded to approximately 5 to 15 percent by weight of asphalt mixture. The Plastiphalt mixtures were designed using the "drop-in" approach and thus, had the same aggregate structure and optimum binder content as the control mixture. Both Plastiphalt and control mixtures were tested for Marshall stability, flow, Marshall quotient value, and density. As the PET dosage increased, the Marshall stability of Plastiphalt mixtures decreased while the flow values increased. At all PET dosages except 5 percent by weight of asphalt mixture, Plastiphalt mixtures had lower Marshall stability and Marshall quotient values than the control mixture. This reduction in mixture stability and deformation resistance was attributed to the low friction between PET granules. At 5 percent dosage, the Plastiphalt mixture had a slightly higher Marshall quotient value than the control mixture. Because of the lower specific gravity of PET compared to aggregate, all Plastiphalt mixtures had lower density values than the control mixture. Finally, it was estimated that for building a 1-km road, replacing 5 percent aggregate (by weight of asphalt mixture) by PET would save 625 tons of natural resources and would use 315 tons of PET, providing significant environmental benefits.

Figure 10. PET Granule Pellets (Hassani et al., 2005)

“Added Value Potential of Processed Plastic Aggregate and ISF Slag in Asphalt” by I. Widyatmok, F. Moulinier, and A. Dunster in *10th International Conference on Asphalt Pavement*, 2006.

Authors	I. Widyatmok, F. Moulinier (Scott Wilson Pavement Engineering Ltd., United Kingdom), and A. Dunster (Building Research Establishment Ltd., United Kingdom)
Sponsor	Unknown
Plastic Type	Not Specified
Plastic Addition Method	Dry Process
Plastic Dosage	20 Percent of Weight of Aggregate
Scope	Laboratory Mixture Testing

This study evaluated the impact of processed plastic aggregate and Imperial Smelting Furnace (ISF) slag on the mechanical properties of asphalt mixtures. The plastic aggregate was produced on a pilot scale from thermal processing of a combination of mixed plastic wastes and fine mineral material. The particle size of the plastic aggregate varied from 5 to 20 mm. The ISF slag was derived from the smelting of zinc ore and had a particle size distribution between coarse and fine sand. A 0/32mm Dense Bitumen Macadam (DBM) base mixture containing a 40/60 penetration grade binder was used for mixture modification. The plastic aggregate was added to replace 20 percent of total aggregate (by weight). The modified mixture had an optimum binder content of 4.6 percent, which was 0.6 percent higher than that of the control mixture. The standard mixing and compaction procedures were followed to produce the modified mixture except that the plastic aggregate was added cold while the regular aggregate was preheated at 180°C for mixing. Both the unmodified control and modified mixtures were tested for volumetrics, load spreading ability, deformation resistance, and moisture resistance. Test results showed that the modified mixture containing the plastic aggregate had a lower density than the control mixture, which was due to the low density and/or possible volume-expansion of the plastic aggregate during mixing. The reduced density of the modified mixture could potentially reduce its hauling and transportation cost due to less fuel consumption, lower emissions, and reduced damage to access roads. From the indirect tensile stiffness modulus (ITSM) test, it was found that the modified mixture had slightly better stiffness characteristics than the control mixture, which could contribute to improved rutting resistance and low-temperature cracking resistance. The repeated load axial test (RLAT) results indicated that the use of plastic aggregate increased the mixture rutting resistance. Finally, the plastic aggregate modified mixture showed acceptable moisture resistance in the ITSM test after artificial moisture conditioning using partial vacuum saturation and up to three freeze-thaw cycles.

"Bitumen/Polyethylene Blends: using m-LLDPEs to Improve Stability and Viscoelastic Properties" by O. Gonzalez, M.E. Munoz, and A. Santamaria in *Rheol Acta*, 2006.

Authors	O. Gonzalez, M.E. Munoz, and A. Santamaria (University of the Basque Country, Spain)
Sponsor	Spanish Government, University of The Basque Country
Plastic Type	High-density Polyethylene (HDPE), Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	1 to 3 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of high-density polyethylene (HDPE) and metallocene catalyzed linear low-density polyethylene (m-LLDPE) for asphalt modification via the wet process. Two traditional HDPE and three m-LLDPE samples obtained from a commercial source were tested. Table 5 summarizes the physico-chemical characteristics of the HDPE and m-LLDPE samples. The base binder used for polyethylene modification was a 60/70 penetration grade binder with an asphaltene content of 20.7 percent. Each HDPE and m-LLDPE sample was added at three dosages: 1, 2, and 3 percent by weight of asphalt binder. A high-shear mixer (1,800 rpm) was used to prepare the HDPE/m-LLDPE modified binders, where mixing was maintained for 6 hours at 180°C. The morphology and storage stability testing indicated that HDPE modified binders were subjective to severe phase separation and storage instability. The use of m-LLDPE for asphalt modification yielded considerably better storage stability results. This improvement in the chemical compatibility of the polyethylene-asphalt system was attributed to the narrower molecular weight distribution and lower melt elasticity of m-LLDPE as compared to HDPE, which facilitated the drop breakup during the mixing process. The addition of m-LLDPE also improved the viscoelasticity properties of the base binder. Finally, the dosage of m-LLDPE suitable for asphalt modification was recommended not to exceed 3 percent in order to prevent phase separation during storage and handling.

Table 5. Physico-chemical Characteristics of HDPE and m-LLDPE Samples (Gonzalez et al., 2006)

Materials	M_w	M_w/M_n	SCB (CH_3/1000C)[a]
HDPE 1	247,500	18.5	–
HDPE 2	171,000	7.7	0.77
m-LLDPE 1	142,000	1.7	10.8
m-LLDPE 2	115,000	1.7	10.5
m-LLDPE 3	96,500	2.5	12.8

[a]Degree of short-chain branching (SCB)

"Study of Recycled Polyethylene Materials as Asphalt Modifiers" by S. Ho, R. Church, K. Klassen, B. Law, D. MacLeod, and L. Zanzotto in *Canadian Journal of Civil Engineering*, 2006.

Authors	S. Ho, R. Church, K. Klassen, B. Law (The University of Calgary, Canada), D. MacLeod (Husky Energy), and L. Zanzotto (The University of Calgary, Canada)
Sponsor	Husky Energy, Natural Sciences and Engineering Research Council of Canada
Plastic Type	Recycled Polyethylene (PE) Wax, Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	Up to 4 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of recycled polyethylene (PE) materials for asphalt modification via the wet process. Combinations of three PE wax and three low-density polyethylene (LDPE) materials were tested. The base binder used for PE modification had a performance grade (PG) of 52-34. A high-shear mixer was used to prepare the PE modified binders at dosages up to 4 percent by weight of asphalt binder. The modified binders were characterized using the Superpave grading system, direct tension test failure strain criteria, phase separation, and fluorescent microscopy. Test results indicated that adding PE wax and LDPE generally improved the rutting resistance but decreased thermal cracking resistance of the asphalt binder, as indicated by an increase in the high-temperature PG but a decrease in the low-temperature PG, respectively. However, not all recycled PE materials yielded the same level of asphalt modification. The low-temperature cracking resistance and phase separation tendency of the modified binders was dependent upon the molecular weight and molecular weight distribution (expressed by the polydispersity index) of the LDPE used; specifically, LDPE with lower molecular weight and wider molecular weight distribution was found more suitable for asphalt modification.

“The Use of Polyethylene in Hot Asphalt Mixtures” by M.T. Awward and L. Shbeeb in *American Journal of Applied Sciences*, 2007.

Authors	M.T. Awward and L. Shbeeb (Al-Balqa Applied University, Jordan)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE)
Plastic Addition Method	Dry Process
Plastic Dosage	6 to 18 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the use of polyethylene (PE) for asphalt mixture modification via the dry process. Two types of PE polymers were tested: low-density polyethylene (LDPE) and high-density polyethylene (HDPE). In the dry process, PE polymers were added directly into the coarse aggregates at 180°C to 190°C. Upon contact and mixing with the aggregates, PE melted and formed a thin film of polymer coating over the surface of the aggregates. The control mixture, designed using the Marshall mix design procedure, had an optimum binder content of 5.4 percent. Each PE polymer was added in two different forms (grinded and not grinded) and at seven polymer dosages (6, 8, 10, 12, 14, 16, and 18 percent by weight of asphalt binder). Both unmodified and PE modified mixtures were tested for bulk density, Marshall stability, Marshall flow, air voids, and voids in mineral aggregates (VMA). Test results showed that in all cases, PE modified mixtures had lower bulk density than the unmodified control mixture. Despite the type and form of PE polymers used, the modified mixtures had the highest bulk density at a dosage of 12 percent. Adding LDPE and HDPE increased the Marshall stability and flow of the control mixture. At all HDPE dosages, the modified mixtures containing grinded polymer had consistently higher Marshall stability than those containing not-grinded polymer; however, no such trend was observed for LDPE modified mixtures. Regarding the mix volumetrics, all PE modified mixtures had higher air voids and VMA than the unmodified control mixture. The air voids and VMA of the modified mixtures gradually decreased as the polymer dosage increased from 6 to 12 percent, while the opposite trend was observed at higher dosages (12 to 18 percent). Finally, the use of 12 percent grinded HDPE was recommended as the optimum mixture modification.

"Development of a Recycled Polymer Modified Binder for Use in Stone Mastic Asphalt" by D. Casey, C. McNally, A. Gibney, and M.D. Gilchrist in *Resources, Conversation and Recycling*, 2008.

Authors	D. Casey, C. McNally (University College Dublin, Ireland), A. Gibney (WSP Ireland Ltd., Ireland), and M.D. Gilchrist (University College Dublin, Ireland)
Sponsor	Enterprise Ireland's Advanced Technologies Research Programme
Plastic Type	Recycled Low-density Polyethylene (LDPE), Recycled Medium-density Polyethylene (MDPE), Recycled High-density Polyethylene (HDPE), Recycled Polypropylene (PP), Recycled Polyvinyl Chloride (PVC), Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Wet Process
Plastic Dosage	Up to 6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study evaluated the use of recycled plastics modified binders in stone mastic asphalt (SMA) applications. The types of recycled plastics included in the study were low-density, medium-density, and high-density polyethylene (LDPE, MDPE, and HDPE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and acrylonitrile butadiene styrene (ABS). An initial evaluation experiment was conducted to determine the feasibility of various recycled plastics for asphalt modification through the wet process. A 200-pentration grade asphalt binder was used. Each recycled plastics sample was added at a dosage of 2 percent by weight of asphalt binder. PET, PVC, ABS, and MDPE were found not suitable for asphalt modification because the modified binders containing these recycled plastics could not achieve desirable homogeneity after mixing. The preparation of homogenous binder blends was successful when up to 5 percent LDPE, HDPE, and PP were used. These successfully modified binders were then tested to determine their viscosity, softening point, and penetration values. Test results indicated that adding LDPE, HDPE, PP (in both mulch and powder forms) increased the viscosity and softening point but reduced the penetration values of the base binder. None of the modified binders were able to meet the agency's performance requirements for polymer modified binders (PMB). To overcome this issue, the LDPE and HDPE modified binders were further optimized through the addition of two chemical additives: diethylenetriamine (DETA) and polyphosphoric acid (PPA). However, the use of DETA did not yield promising results; modified binders containing 1 and 2 percent DETA showed reduced storage stability. On the other hand, adding 0.8 percent PPA was successful, improving the storage stability and performance properties of LDPE and HDPE modified binders. Based on the test results, the modified binder containing 4 percent HDPE and 0.8 percent PPA was selected as the optimal binder blend. Finally, the wheel tracking test and indirect tensile fatigue test were conducted to evaluate the rutting and fatigue resistance of SMA mixes containing three different binders: an unmodified binder, a proprietary elastomeric PMB, and the optimal binder blend developed in this study. Test results showed that the HDPE plus

PPA modified mixture did not perform as well as the proprietary PMB mixture, but it did outperform the unmodified control mixture.

"Evaluation of Asphalt Pavements Constructed using Novophalt" by M.G.M. Al-Taher, A. Mohamady, and M.A. Shalaby in *Emirates Journal of Engineering Research*, 2008.

Authors	M.G.M. Al-Taher, A. Mohamady, and M.A. Shalaby (Zagazig University, Egypt)
Sponsor	Unknown
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	Not Specified
Scope	Field Project, Laboratory Mixture Testing, Cost Analysis

This study evaluated the field performance of an asphalt pavement constructed using Novophalt®. For performance comparison, a control pavement section using an unmodified asphalt binder was also included. Both pavement sections were overlaid in 2001 and had similar pavement structure, climatic, and traffic conditions. Five rounds of pavement distress surveys were conducted from 2004 to 2008. For each survey, the pavement condition index (PCI) value was calculated as an overall pavement performance indicator. Over the five-year period, six major types of pavement distresses were observed: alligator cracking, bleeding, block cracking, longitudinal and transverse cracking, rutting, and weathering/raveling. As shown in Table 6, the Novophalt® section significantly outperformed the control section in terms of rutting and bleeding resistance. However, the opposite trend was observed for their cracking performance, where the Novophalt® section had slightly more alligator, longitudinal, and transverse cracking. These performance differences were attributed to the binder stiffening and embrittlement effect as a result of Novophalt® polyethylene modification. Figure 11 compares the projected PCI deterioration curves of the two pavement sections. As shown, the Novophalt® section had better overall performance, as indicated by consistently higher PCI values, than the control section. Using a minimum PCI threshold of 25 percent and typical local traffic conditions, the Novophalt® section was expected to last 12.8 years while the control section could only last 8.3 years. Field cores were taken from both pavements at locations with no distress, rutting distress, and cracking distress, respectively, and then tested for Marshall stability and flow. Test results indicated that the low Marshall stability of asphalt mixtures was likely the cause of rutting in the field while cracking was possibly induced by the large difference in the Marshall stability between surface and base mixtures. Finally, a simplified cost analysis was conducted to determine the economic benefits of using Novophalt®, which concluded that the initial cost of Novophalt® pavement was 19 percent higher than the control pavement; however, its life-cycle cost was 17 percent lower due to improved pavement performance and extended pavement service life.

Table 6. Distress Deduct Values of Novophalt® *versus* Control Pavement Sections (Al-Taher et al., 2008)

Asphalt type		Novophalt						Normal					
Distress name		Alligator Crack (m^2)	Bleeding (m^2)	Block Crack (m^2)	Long&Trans Crack (m)	Rutting (m^2)	Weathering /Raveling (m^2	Alligator Crack (m^2)	Bleeding (m^2)	Block Crack (m^2)	Long&Trans Crack (m)	Rutting (m^2)	Weathering /Raveling (m^2
Date	6/2004	1.0	0.34	0.06	0.63	0.00	1.59	0.00	6.25	0.00	0.75	5.25	1.50
	6/2005	2.8	0.34	0.12	3.13	0.30	1.61	0.53	4.06	0.00	0.89	7.22	1.03
	1/2006	7.2	0.33	0.58	5.61	0.84	2.04	2.53	5.67	0.08	2.22	14.9	1.58
	6/2006	8.4	0.39	0.69	7.32	1.07	2.18	3.28	5.47	0.50	2.50	18.1	1.69
	1/2008	11.2	0.42	1.07	9.58	1.76	3.19	4.56	5.36	0.72	3.67	32.0	2.06

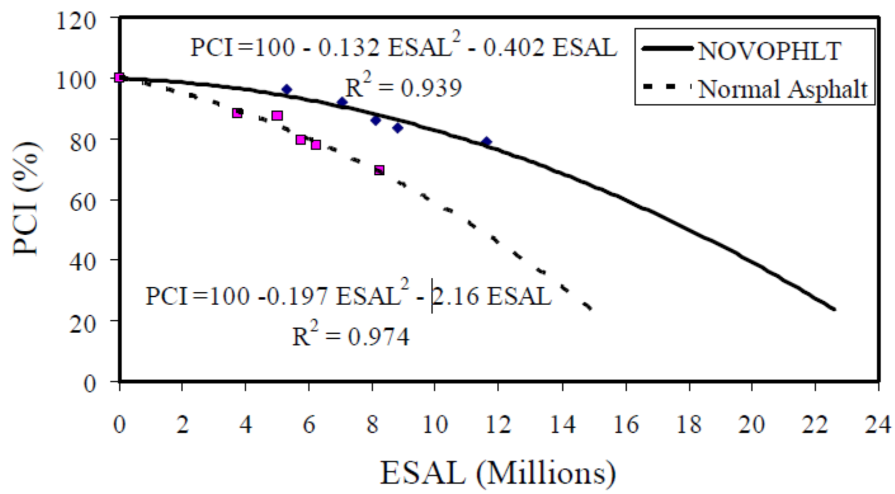


Figure 11. Projected PCI Deterioration Curves of Novophalt® *versus* Control Pavement Sections (Al-Taher et al., 2008)

"Evaluation of Thermal and Mechanical Properties of Recycled Polyethylene Modified Bitumen" by C. Fuentes-Auden, J.A. Sandoval, A. Jerez, F.J. Navarro, F.J. Martinez-Boza, P. Partal, and C. Gallegos in *Polymer Testing*, 2008.

Authors	C. Fuentes-Auden, J.A. Sandoval, A. Jerez, F.J. Navarro, F.J. Martinez-Boza, P. Partal, and C. Gallegos (Universidad de Huelva, Spain)
Sponsor	MMA programme, Ministerio de Medio Ambiente, Spain
Plastic Type	Blend of Recycled Low-density Polyethylene (LDPE), Recycled Linear Low-density Polyethylene (LLDPE), and Recycled Polypropylene (PP)
Plastic Addition Method	Wet Process
Plastic Dosage	Up to 50 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the thermal and mechanical properties of asphalt binders modified with recycled PE via the wet process. The recycled PE sample used was a blend of LDPE, LLDPE, and PP, with a specific gravity of 0.930, a melt flow index of 0.80, and an ash content of 0.8 percent. The base binder used for polyethylene modification had a 150/200 penetration grade. Iatroscan analysis indicated that the binder was composed of 8.0 percent saturates, 53.3 percent aromatics, 29.8 percent resins, and 8.9 percent asphaltenes. A high-shear mixer was used to prepare asphalt binders modified with up to 25 percent recycled PE, while a modular batch mixing system was used at the 50 percent recycled PE content. After asphalt modification, the steady flow, dynamic temperature sweep, dynamic mechanical thermal analysis, modulated differential scanning calorimetry, direct tensile, and optical microscopy tests were conducted to characterize the thermal and mechanical properties of recycled PE modified binders. Test results showed that at intermediate and high in-service temperature ranges, PE modification increased the viscosity and shear modulus of the base binder, while decreasing its thermal susceptibility. Adding recycled PE also lowered the mechanical glass transition temperature of the base binder. These results indicated that asphalt binders after recycled modification were expected to have better resistance to permanent deformation, thermal cracking, and fatigue cracking. Figure 12 presents the microscopy images of asphalt binders containing different recycled PE contents. When the PE content was less than 15 percent, the modified binders showed a dispersion of discontinuous polymer-rich phase in a continuous asphalt-rich phase; however, at 15 percent content or higher, the modified binders showed a dispersion of asphalt-rich droplets in the continuous polymer-rich phase. This phase inversion phenomenon was also identified through the evaluation of binder rheological properties. Finally, the viscous flow curves indicated that up to 5 percent recycled PE could be used to modify asphalt binders for paving applications, while higher contents were more suitable for roofing applications.

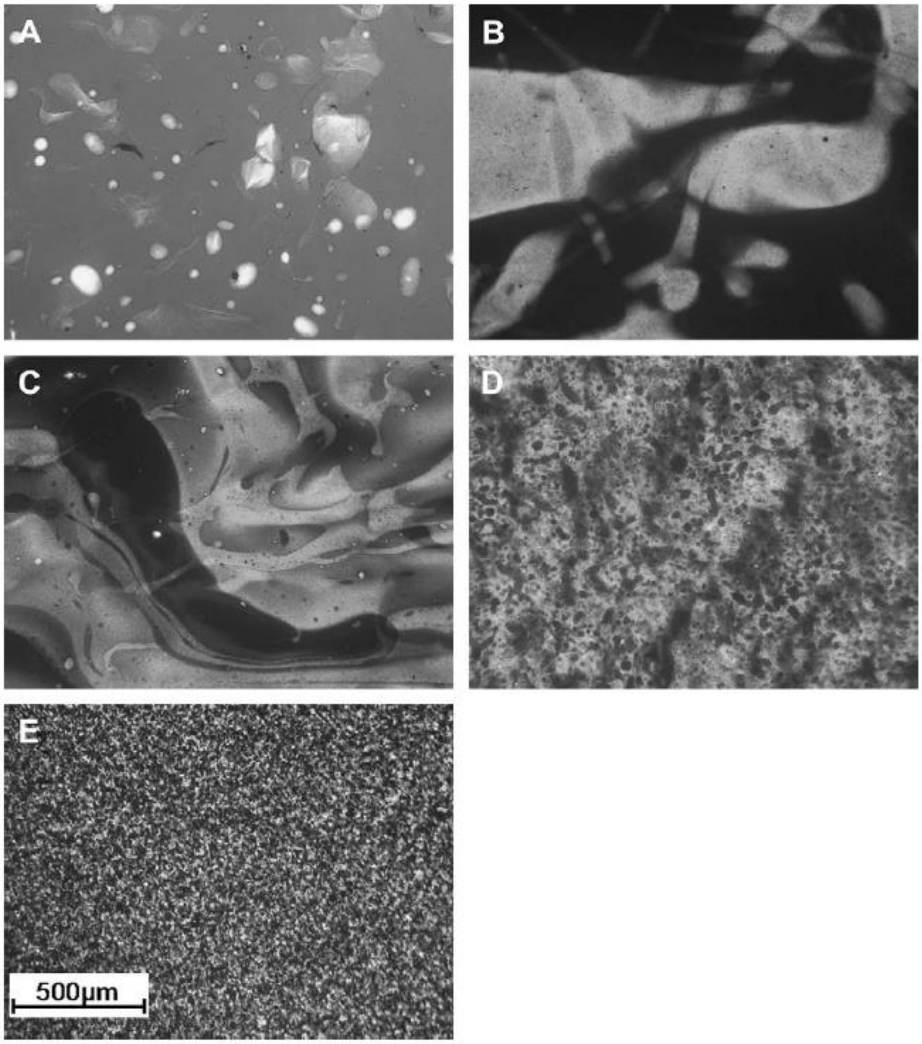


Figure 12. Microscopy Images of Asphalt Binders Modified with Recycled Polyethylene at Various Dosages; (A) 2 percent, (B) 5 percent, (C) 15 percent, (D) 25 percent, and (E) 50 percent (Fuentes-Auden et al., 2008)

"Performance Evaluation of Polymer Coated Bitumen Built Roads" by Central Pollution Control Board, 2008.

Authors	Central Pollution Control Board, Ministry of Environment & Forests, India
Sponsor	Central Pollution Control Board
Plastic Type	Polyethylene (PE), Polypropylene (PP), Polystyrene (PS)
Plastic Addition Method	Dry Process
Plastic Dosage	10 to 12 Percent by Weight of Asphalt Binder
Scope	Field Project

This study evaluated the field performance of asphalt pavements constructed using plastics waste-coated aggregate (PCA) asphalt mixtures. Different commercial plastic materials including polyethylene (PE) film, PE foam, polypropylene (PP), polystyrene (PS), and teacups were collected and tested for softening point. For most plastic polymers tested, the softening point was below 170°C. The only two exceptions were polyvinyl chloride (PVC) and polyethylene terephthalate (PET). Compression and bending strength tests were also conducted on plastic-coated aggregates. Test results showed that the aggregate strength increased as the percentage of plastics increased. Also, the coated plastics did not leach out by the leaching liquid (i.e., 5% acetic acid).

The study also discussed two processes of constructing asphalt pavements using PCA asphalt mixtures in India. In the first process, the pavements were constructed using both a mini hot mix plant and a central mixing plant (CMP). For mix production, the aggregates were first heated to 170°C in the cylindrical drum and then transferred to the puddling compartment where the shredded plastics (sized between 1.18mm and 4.36mm) were added. The plastics melted and formed a thin film over the surface of the aggregates within 30 to 45 seconds of mixing. Then, the asphalt binder was added to the PCA in the puddling chamber for further mixing. Finally, the mix was transferred to the paving site, paved, and compacted. The second process was recommended mainly for the construction of long-distance pavements using a CMP. In this process, a mechanical device was needed to mix the plastics waste and aggregates in the cylindrical drum before the asphalt binder was introduced. During the production and construction process, the mix needed to be continuously blended to ensure uniform distribution of plastics and better binding with the aggregates and asphalt binder.

From 2002 to 2007, more than 35 pavement sections using PCA asphalt mixtures were constructed spreading around 1,500km in Tamil Nadu, India. Of those, five sections were selected for evaluation of pavement roughness, skid resistance, macro texture, field density, deflection, gradation, and distress condition in this study. A control pavement section with a non-PCA asphalt mixture was included for performance comparison. Table 7 summarizes the project information and field performance data of the six selected pavement sections. Based on the consolidated results from structural evaluation, functional evaluation, and conditional evaluation, the five pavement sections using PCA asphalt mixtures performed well despite their age and various environmental conditions, with no cracking, potholes, raveling, edge flaw, or deformation distresses observed. These sections also outperformed the control pavement section in terms of overall field performance. Finally, laboratory testing indicated that coating of plastics improved the strength and quality of aggregates, which yielded asphalt mixtures with better pavement performance.

Table 7. Summary of Project Information and Field Performance Data of Six Selected Pavement Sections (Central Pollution Control Board, 2008)

Section	Location	Year Constructed	Binder Penetration Grade	Source/Type of Plastics Waste	Percentage of Plastics Used	Roughness (mm/km)	Skid Number	Sand Texture Depth (mm)	Field Density	Rebound Deflection (mm)
1	Chennai	2002	60/70	Municipal Waste – PE and PP Mix	12	2,700	41	0.63	2.55	0.85
2	Erode	2003	60/70	Municipal Waste – PP Mix	12	3,785	45	0.70	2.62	0.60
3	Madurai	2004	80/100	Municipal Waste – PE and PP Mix	10	3,005	41	0.66	2.75	0.84
4	Madurai	2005	80/100	Municipal Waste – PE and PP Mix	12	3,891	45	0.50	2.89	0.86
5	Madurai	2006	80/100	Municipal Waste – PE	10	3,100	45	0.65	2.86	0.86
6	Madurai	2002	80/100	N/A	N/A	5,200	76	0.83	2.33	1.55

“Effect of Polyethylene on Life of Flexible Pavements” by A.I. Al-Hadidy and Y. Tan in *Construction and Building Materials*, 2009.

Authors	A.I. Al-Hadidy and Y. Tan (Harbin Institute of Technology, China)
Sponsor	National Natural Science Foundation, Research Fund for the Doctoral Program of Higher Education of China
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2 to 8 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing, Laboratory Binder Testing, Pavement Design

This study evaluated the use of pyrolysis low-density polyethylene (LDPE) for asphalt modification via the wet process. The base binder used had a 50/60 penetration grade. The LDPE sample was obtained from a commercial source but subjected to mechanical grinding and thermal degradation (Figure 13) prior to being used for asphalt modification. The processed LDPE was added at four different dosages: 2, 4, 6, and 8 percent by weight of asphalt binder. For the preparation of LDPE modified binders, a high-shear mixer (1,750 rpm) was used to blend the LDPE into asphalt binder for 3 to 5 minutes at approximately 160°C. In the first phase of the study, laboratory binder tests were conducted to determine the physical and rheological properties of LDPE modified binders. Test results showed that adding LDPE stiffened the asphalt binder. LDPE modified binders had lower penetration and ductility but higher softening point values than the unmodified control binder. Adding LDPE also reduced the binder’s susceptibility to temperature changes and mass loss due to heat and air. Finally, light microscopy confirmed adequate compatibility between the LDPE and asphalt binder used.

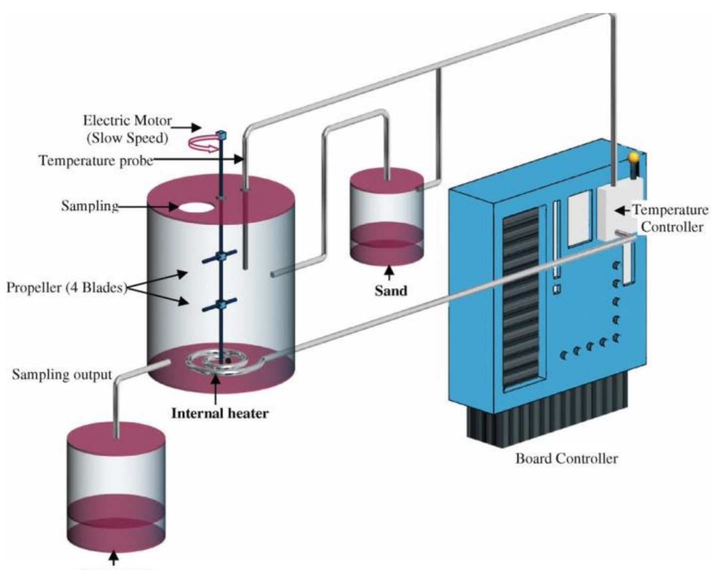


Figure 13. Schematic Illustration of the PE Thermal Degradation Process (Al-Hadidy and Tan, 2009)

The second phase of the study evaluated the impact of LDPE modification on the engineering properties of stone mastic asphalt (SMA) mixtures. The base mixture was designed following the Marshall mix design procedure, which resulted in an optimum binder content of 5.8 percent at 50 Marshall blows. A “drop-in” approach was then used to prepare LDPE modified SMA mixtures at various polymer dosages. Both unmodified and LDPE mixtures were tested using the Marshall test, tensile strength ratio (TSR), and low-temperature bending beam flexural strength (BBFS) tests. The Marshall stability of the modified mixtures increased but the flow value decreased as the LDPE dosage increased up to 6 percent, while the opposite trend was observed at a higher LDPE dosage. Adding LDPE also improved the mixture’s moisture resistance in the TSR test. Finally, the low-temperature BBFS results indicated that the 6 percent LDPE modified mixture was more resistant to thermal cracking than the unmodified control mixture.

In the final phase of the study, mechanistic-empirical pavement design analyses were conducted to evaluate the benefits of LDPE modification in terms of reduction in layer thickness and extension in pavement service life. Two design alternatives were considered using a multi-layer elastic analysis program; one assumed the same layer thickness while the other assumed the same pavement service life for pavement sections using unmodified versus LDPE modified SMA mixtures. Results from both analyses showed that LDPE modified pavement sections significantly outperformed the unmodified pavement sections. The improvement in predicted pavement performance was mainly attributed to the increased mixture stiffness due to LDPE modification.

"Modification of a 14mm Asphalt Concrete Surfacing Using Rap and Waste HDPE Plastic" by I. Aschuri and D. Woodward in *International Journal of Pavements*, 2010.

Authors	I. Aschuri (National Institute of Technology, Indonesia) and D. Woodward (University of Ulster, Ireland)
Sponsor	Unknown
Plastic Type	Recycled High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	0.75 to 3 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study assessed the use of waste HDPE plastic and recycled asphalt pavement (RAP) for improving the performance of a 14mm asphalt surface mixture. HDPE was collected from milk cartons and cut into small pieces approximately 2 x 2mm in size. It had a specific gravity of 0.94 to 0.95, a melting point of 120 to 130°C, and a tensile strength of 31.35 MPa. The base binder used for HDPE modification had a 60/70 penetration grade. The dosage of HDPE used varied from 0.75 to 3 percent by weight of asphalt binder. Binder test results indicated that adding HDPE reduced the penetration but increased the softening point of the base binder, which indicated a stiffening effect of asphalt binder due to HDPE modification. Penetration Index (PI) was used to evaluate the temperature susceptibility of each modified binder. The PI of HDPE modified binders was found to increase as the dosage of HDPE increased. This suggested that asphalt modification using waste HDPE might have a beneficial effect on the temperature susceptibility of asphalt binder, providing higher stiffness at higher in-service temperatures compared to unmodified binder. The bitumen stiffness modulus (S_b) was determined using the Van der Poel nomograph. It was found that the binder stiffness modulus increased as the dosage of HDPE increased. Asphalt binders modified with waste HDPE had a significant increase in the slope of the stiffness modulus versus modifier dosage curve. Based on the temperature susceptibility and stiffness modulus results, 1.5 percent was selected as the optimum HDPE dosage for further evaluation through mixture performance testing. A total of four mixtures were tested, including one unmodified control mixture with no RAP, a HDPE modified mixture with no RAP, and two HDPE modified mixtures with 30 and 60 percent RAP. All mixtures were prepared with the same optimum binder content of 6 percent. From the indirect tensile stiffness modulus (ITSM) test, it was found that adding HDPE and RAP increased the stiffness of asphalt mixtures at temperatures ranging from 20 to 40°C. The repeated load axial test (RLAT) and British wheel tracking test (WTT) results showed that HDPE modified mixtures with and without RAP outperformed the unmodified control mixture in terms of rutting resistance. Use of HPDE for asphalt modification increased fatigue life at a tensile strain of 100 microstrain in the indirect tensile fatigue test (IDFT), while the opposite trend was observed for the addition of RAP. Additionally, specimen air voids were found to have a significant impact on the IDFT results. Finally, mix overall durability was evaluated using retained Marshall stability, retained ITSM, and the Cantabro test. Test results showed that asphalt mixtures modified with HDPE and RAP were less susceptible to moisture damage and disintegration and thus, more durable than the unmodified control mixture.

"Behavior of Reclaimed Polyethylene Modified Asphalt Cement for Paving Purpose" by V.S. Punith and A. Veeraragavan in *Journal of Materials in Civil Engineering*, 2011.

Authors	V.S. Punith (Clemson University, United States) and A. Veeraragavan (Indian Institute of Technology Madras, India)
Sponsor	King Fahd University of Petroleum and Minerals, Saudi Arabia
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2.5 to 10 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of recycled low-density polyethylene (LDPE) for asphalt modification via the wet process. The LDPE was obtained from domestic waste carry bags and shredded into 2 mm x 2 mm pieces, as shown in Figure 14. The LDPE had a specific gravity of 0.95 and a melting temperature of 130°C. The base binder used for LDPE modification had an 80/100 penetration grade. LDPE was added at four dosages: 2.5, 5.0, 7.5, and 10.0 percent by weight of asphalt binder. For the preparation of LDPE modified binders, a high-shear mixer (3,500 rpm) was used to blend the LDPE into asphalt binder for 20 minutes at approximately 165°C. It was found that adding LDPE stiffened the asphalt binder; in all cases, LDPE modified binders had reduced penetration and ductility values but increased softening point as compared to the base binder. The changes in these binder properties became more significant as the LDPE dosage increased. Although LDPE is a plastomeric polymer by nature, LDPE modified binders showed better elasticity than the base binder in the elastic recovery test. The addition of LDPE reduced the binder's susceptibility to mass loss on heating and oxidative aging. LDPE modified binders showed no sign of phase separation in the storage stability test; the variation between the top and bottom cigar-tube binder portions was less than 3 percent for penetration and softening point measurements. *[Commentary: these results contradict the findings of many other relevant studies]*. Thermogravimetric analysis indicated that LDPE modification had no significant impact on the thermal degradation behavior of the base binder. Finally, dynamic shear rheometer test results indicated that adding LDPE increased binder stiffness, elasticity, and high-temperature rutting resistance.

Figure 14. Shredded LDPE Sample (Punith and Veeraragavan, 2011)

"Effect of Waste Polymer Modifier on the Properties of Bituminous Concrete Mixes" by T. Sangita, A. Khan, and D.K. Sabina in *Construction and Building Materials*, 2011.

Authors	T. Sangita (Central Road Research Institute, India), A. Khan (Jamia Millia Islamia, India), and D.K. Sabina (Indian Institute of Technology Delhi, India)
Sponsor	Unknown
Plastic Type	Blend of Shredded Nitrile Rubber and Recycled Polyethylene (PE)
Plastic Addition Method	Dry Process
Plastic Dosage	6, 8, 12, and 15 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the effect of waste polymer modifier (WPM) on the engineering properties of asphalt mixtures. The WPM used was a blend of shredded nitrile rubber and recycled polyethylene (PE) in 1:4 ratio, which had approximately 98 percent passing the 2.36 mm sieve and 73 percent passing the 1.18 mm sieve. WPM was added using the dry process to coat the surface of aggregates, which were then mixed with the asphalt binder for producing WPM modified mixtures. The WPM dosages used were 6, 8, 12, and 15 percent by weight of asphalt binder. All WPM modified mixtures were produced using a "drop-in" approach and thus, had the same aggregate structure and optimum binder content as the control mixture. Based on the Marshall stability test results, 8 percent was selected as the optimum dosage for WPM. Then, the optimum WPM modified mixture was tested in retained stability, indirect tensile strength, creep stiffness, wheel tracking test, and resilient modulus tests. Test results indicated that adding WPM increased the stiffness of the control mixture and improved its resistance to permanent deformation and moisture damage.

"Laboratory Evaluation of HMA with High Density Polyethylene as a Modifier" by A. Moatasim, P. Cheng, and A.I. Al-Hadidy in *Construction and Building Materials*, 2011.

Authors	A. Moatasim, P. Cheng (Northeast Forestry University, China), and A.I. Al-Hadidy (Mosul University, Iraq)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	1 to 7 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the use of high-density polyethylene (HDPE) for asphalt modification via the wet process. The HDPE sample was provided in pellet form and had a specific gravity of 0.943 and a melting temperature of 149°C. The base binder used for HDPE modification had an 80/100 penetration grade. Four different dosages of HDPE were tested: 1, 3, 5, and 7 percent by weight of asphalt binder. For the preparation of HDPE modified binders, a high-shear mixer (3,000 rpm) was used to blend the HDPE into asphalt binder for 2 hours at 170°C. Laboratory binder tests were first conducted to determine the physical and rheological properties of HDPE modified binders. Test results showed that adding HDPE stiffened the asphalt binder, as indicated by reduced penetration and ductility values and increased softening points. The stiffening effect was more significant at higher HDPE dosages. HDPE modified binders were also found less susceptible to temperature changes and mass loss due to heat and air as compared to the base binder. Then, the Marshall stability, tensile strength ratio (TSR), resilient modulus (M_R), and low-temperature bending beam flexural strength (BBFS) tests were conducted to determine the impact of HDPE modification on the engineering properties of asphalt mixtures. To this end, a Marshall mix design was followed to produce HDPE modified mixtures at different polymer dosages. The Marshall stability test results showed a general trend that the stability and Marshall Quotient (MQ) increased but flow decreased as the HDPE dosage increased, which indicated enhanced rutting resistance due to HDPE modification. HDPE modified mixtures also outperformed the unmodified control mixture in terms of moisture resistance in the TSR test; this improvement was attributed to enhanced adhesion between the aggregates and asphalt binder after HDPE modification. Furthermore, adding HPDE showed a consistent impact of increasing the M_R stiffness of asphalt mixtures at 25°C. Finally, the 5 percent HDPE modified mixture had higher modulus of rupture and stiffness modulus at 0°C and -10°C in the low-temperature BBFS test than the unmodified mixture, which indicated potential improvement in thermal cracking resistance.

“Using Waste Plastic Bottles as Additive for Stone Mastic Asphalt” by E. Ahmadinia, M. Zargar, M.R. Karim, M. Abdelaziz, and P. Shafigh in *Materials and Design*, 2011.

Authors	E. Ahmadinia, M. Zargar, M.R. Karim, M. Abdelaziz, P. Shafigh (University of Malaya, Malaysia)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	2, 4, 6, 8, and 10 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study investigated the effect of incorporating waste plastic bottles on the engineering properties of stone mastic asphalt (SMA) mixtures prepared with crushed granite aggregate. The primary polymer makeup of the plastic bottles was PET. A dry process was used for mixture modification, where chopped PET particles were added and mixed with the mixture for 2 minutes at 160°C after the aggregates were mixed with asphalt binder. A total of 25 mixtures were prepared, including five binder contents ranging from 5 to 7 percent and five PET dosages at each binder content (2, 4, 6, 8, and 10 percent by weight of asphalt binder). The asphalt binder had an 80/100 penetration grade. Each mixture was tested for Marshall stability, flow, Marshall quotient value, and volumetric properties. It was found that the Marshall stability values of PET modified mixtures increased as the PET dosage increased up to 6 percent, after which they started to decrease. In most cases, the Marshall stability values of PET modified mixtures were higher than that of the unmodified control mixture, which was attributed to better adhesion among the materials in the mix. On the other hand, the Marshall flow values decreased as the PET dosage increased up to approximately 2 to 4 percent, after which they started to increase. Modified mixtures containing 2, 4, and 6 percent PET had higher Marshall quotient values, indicating increased stiffness and deformation resistance, than the control mixture, while the opposite trend was observed for those at higher PET dosages. Based on these results, 6 percent was selected as the optimum PET dosage for mixture modification. Regarding volumetrics, adding PET generally decreased the bulk specific gravity of the control mixture while increasing its air voids and voids in mineral aggregate. Nevertheless, all PET modified mixtures met the standard volumetric requirements.

"A Technique to Dispose Waste Plastics in an Ecofriendly Way – Application in Construction of Flexible Pavements" by R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, and R. Velkennedy in *Construction and Building Materials*, 2012.

Authors	R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, and R. Velkennedy (Thiagarajar College of Engineering, India)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE), Recycled Polypropylene (PP), Recycled Polystyrene (PS)
Plastic Addition Method	Dry Process
Plastic Dosage	5 to 20 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing, Field Project, Cost Analysis

This study evaluated the use of waste plastics for asphalt mixture modification via the dry process. Three types of waste plastics were tested: polyethylene (PE), polypropylene (PP), and polystyrene (PS). In the dry process, waste plastics were added into the aggregates prior to being mixed with the asphalt binder. When in contact with preheated aggregates at 160°C, waste plastics melted and formed a thin film over the surface of the aggregates. In this study, waste plastics were added at dosages ranging from 5 to 20 percent by weight of asphalt binder. Based on the aggregate test results, plastics-coated aggregates (PCA) had improved soundness, abrasion resistance, impact resistance, and crushing resistance, as well as reduced water absorption compared to the uncoated aggregates. The use of PCA also increased the Marshall stability of asphalt mixtures. The study also monitored the field performance of five paving projects constructed using PCA modified mixtures between 2002 and 2006. For each project, rebound deflection, smoothness, field density, skid resistance, and texture depth were measured. Field performance data showed that PCA modified mixtures performed better or equivalent to the control mixtures. At the time of pavement condition survey, no rutting, cracking, pothole, or edge flaw was observed for the projects using PCA modified mixtures. Finally, a simplified cost analysis was conducted, which concluded that using PCA could save the material cost of asphalt mixtures by approximately 10 percent.

"Use of Recycled Material from the Banana Bags Protection as an Improver of the Asphalt Properties and Reduction of the Plastic Waste. Costa Rica and Colombian Experience" by R.E. V. Villegas, W.D.F. Gomez, L.G.L. Salazar, and F.A.R. Lizcano, 2012.

Authors	R.E.V. Villegas (Universidad de Costa Rica, Costa Rica), W.D.F. Gomez (Universidad Distrital Francisco José de Caldas, Colombia), L.G.L. Salazar (Universidad de Costa Rica, Costa Rica), and F.A.R. Lizcano (Pontificia Universidad Javeriana, Colombia)
Sponsor	Unknown
Plastic Type	Polyethylene from Waste Banana Bags
Plastic Addition Method	Wet Process
Plastic Dosage	3% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

In the banana production industry, polyethylene wraps are used to protect bananas from disease and damage. This research evaluated the use of waste banana bags for asphalt binder modification via the wet process. A common asphalt binder used in Costa Rica, AC-30, was used in this research. The waste banana bags were cut into 4 cm squares and added into the asphalt binder at a 3% dosage rate (by weight of asphalt binder) using a low shear mixer for two hours at 160°C. The Superpave performance grade (PG), multiple stress creep recovery (MSCR), Raman spectroscopy (RS), thermogravimetric analysis (TGA), differential scanning calorimeter (DSC), and Fourier transform infrared spectrometry (FTIR) tests were conducted to evaluate the properties of the modified binders.

Test results indicated that this waste plastic material had sufficient distribution within the asphalt binder and behaved similarly to styrene-butadiene-styrene (SBS) in terms of the impact on asphalt binder properties. The calorimetric tests indicated that the fusion and degradation of the waste banana bags started at 150°C and 425°C, respectively. The binder creep test results indicated that this plastic material improved the binder's permanent deformation by 50%. The MSCR Jnr results did not indicate any difference between the waste banana bags and other polymer modifiers [i.e., SBS and styrene-butadiene-rubber (SBR)] when used for asphalt binder modification. Finally, this study recommended using asphalt binders modified with waste banana bags for normal traffic loading conditions such as low-volume roads, parking lots for passenger vehicles, and bicycle lanes.

“Laboratory Investigation on Use of Fly Ash Plastic Waste Composite In Stone Matrix Asphalt” by U.D. Rongali, A. Chourasiya, G. Singh, and P.K. Jain in *25th ARRB Conference – Shaping the Future: Linking Policy, Research and Outcome*s, 2012.

Authors	U.D. Rongali, A. Chourasiya, G. Singh, and P.K. Jain (Central Road Research Institute New Delhi, India)
Sponsor	Unknown
Plastic Type	Not Specified
Plastic Addition Method	Dry Process
Plastic Dosage	8 Percent by Weight of Fly Ash
Scope	Laboratory Mixture Testing

This study investigated the laboratory performance of Stone Matrix Asphalt (SMA) mixtures containing fly ash and optimized composite made up of ash-plastic waste (shredded with particle size between 2-8 mm). An asphalt binder with a 50/70 penetration grade was used. The utilized plastic waste had a melting temperature of 124 to 129°C and an initial decomposition temperature of 399°C. For the preparation of SMA mixtures, the plastic waste without any polyvinyl chloride was added to heated fly ash and mixed thoroughly at 160 to 170°C. The dosage of plastic waste was kept at 8 percent by weight of fly ash. The tensile strength ratio and wheel-tracking test results showed that SMA mixtures containing the plastic waste composite filler had better moisture resistance and rutting resistance than those containing plain fly ash as filler. The use of fly ash-plastic waste as filler also improved the stiffness of SMA mixtures in the resilient modulus test. For mechanistic analysis, KENPAVE software was employed to calculate the critical strains within a pavement structure and estimate the pavement life. Analysis results indicated that for a SMA mixture containing fly ash-plastic waste as filler, its tensile strain at bottom of the asphalt layer and compressive strain on top of the subgrade reduced by 32 percent and 11 percent, respectively, which resulted in a Traffic Benefit Ratio (TBR) of 1.77.

“Recycling of Banana Production Waste Bags in Bitumens: A Green Alternative” by R.E. Villegas-Villegas, L.G. Loria-Salazar, J.P. Aguiar-Moya, W.D. Fernandez-Gomez, and F.A. Reyes-Lizcano in the *Proceedings of the 5th Eurasphalt & Eurobitume Congress*, 2012.

Authors	R.E. Villegas-Villegas, L.G. Loria-Salazar, J.P. Aguiar-Moya (Universidad de Costa Rica, Costa Rica), W.D. Fernandez-Gomez (Universidad Distrital Francisco José de Caldas, Colombia), and F.A. Reyes-Lizcano (Pontificia Universidad Javeriana, Colombia)
Sponsor	Unknown
Plastic Type	Recycled High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	3 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing, Laboratory Binder Testing

This study evaluated the use of recycled banana production waste bags for asphalt modification via the wet process. The waste bags were collected from local banana plantations and processed in the laboratory, where they were initially blown with air to remove solid particles attached to the surface of the bags, washed with tetrahydrofuran and acetone for removal of organic compounds, and then dried and cut into 4 cm x 4 cm squares (Figure 15). Differential scanning calorimetry analysis identified the main polymer resin makeup of the banana bags as high-density polyethylene (HDPE). The dosage of banana bags used for asphalt modification was 3 percent by weight of asphalt binder. For the preparation of modified binders, a low-shear mixer was used to blend the banana bags into asphalt binder for 2 hours at 160°C. From the thermogravimetry test, the banana bags started thermal degradation at 150°C and ended at around 450°C. The modified binder met the Superpave PG 70-xx requirements, while the base binder was graded as PG 64-xx. The repeated creep and multiple stress creep tests indicated that adding banana bags significantly improved the binder’s resistance to high-temperature permanent deformation. However, use of banana bags for asphalt modification had no impact on the fatigue resistance of the base binder. Mixture performance tests were also conducted to determine the impact of banana bags on the performance properties of asphalt mixtures. The modified mixture was designed using the “drop-in” approach and thus had the same aggregate structure and optimum binder content as the unmodified control mixture. From the tensile strength ratio, resilient modulus, and Asphalt Pavement Analyzer tests, it was found that adding banana bags increased the mixture stiffness and improved its resistance to rutting and moisture damage.

Figure 15. Processed Banana Bags Used for Asphalt Modification (Villegas-Villegas et al., 2012)

"Utilization of Waste Plastic in Asphalting of Roads" by A. Gawande, G.S. Zamre, V.C. Renge, G.R. Bharsakale, and S. Tayde in *Scientific Reviews & Chemical Communications*, 2012.

Authors	A. Gawande, G.S. Zamre, V.C. Renge, G.R. Bharsakale, and S. Tayde (College of Engineering and Technology, India)
Sponsor	Unknown
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Literature Review

This review article identifies two approaches of modifying asphalt mixtures using waste plastics: the dry process and the wet process. In the dry process, recycled plastics in shredded film or pellet form are added to the aggregates prior to being mixed with the asphalt binder. When in contact with the aggregates, the plastics will melt and form a thin film over the surface of the aggregates. As compared to traditional uncoated aggregates, plastics-coated aggregates are claimed to have enhanced surface properties, such as reduced moisture absorption, increased soundness and increased abrasion resistance, and can produce asphalt mixtures with better resistance to rutting, fatigue damage, and moisture damage. With the dry process, up to 15 percent plastics by weight of asphalt binder can be used. In the wet process, recycled plastics need to be first ground into powder form and then blended into asphalt binder using a shear mixer. Typically, up to 6 to 8 percent plastics by weight of asphalt binder can be added. Plastics modified binders prepared using the wet process typically have higher stiffness and viscosity and better rutting resistance than the unmodified binders. Additionally, adding recycled plastics via the wet process can significantly improve the Marshall stability of asphalt mixtures. The review article summarizes the reported advantages and disadvantages of the two processes of recycling plastics in asphalt and discusses three case studies on the use of recycled plastics in asphalt pavements. The first one was a laboratory study that evaluated the use of recycled plastics for asphalt modification via the wet process. This study found that adding 8.8 percent processed plastics by weight of asphalt binder significantly improved the stability, strength, and fatigue life of asphalt mixtures; however, details regarding the experimental design and test results of the study were not provided. The other two case studies were field projects constructed using asphalt mixtures modified with recycled plastics in India. Although both projects were reported to have satisfactory field performance, detailed information about the age of the pavements and surface distress conditions was not discussed.

“Asphalt/Polyethylene Blends: Rheological Properties, Microstructure and Viscosity Modeling” by M.A. Vargas, M.A. Vargas, A. Sanchez-Solis, and O. Manero in *Construction and Building Materials*, 2013.

Authors	M.A. Vargas, M.A. Vargas, A. Sanchez-Solis, and O. Manero (Universidad Nacional Autónoma de México, Mexico)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Bimodal Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	4 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of polyethylene and grafted polyethylene for asphalt modification via the wet process. A total of six polyethylene samples were tested, including three commercial high-density polyethylene (HDPE), low-density polyethylene (LDPE), and bimodal polyethylene (BHDPE), and three maleic anhydride (MA)-grafted polyethylene polymers obtained by reactive extrusion. The base binder used for polyethylene modification had an AC-20 grade. For the preparation of polymer modified binders, a low-shear mixer (500 rpm) was used to blend polyethylene into asphalt binder. The shear mixing process was maintained for 4 hours at 180°C until a homogeneous binder blend was achieved. Storage stability and fluorescence microscopy tests were first conducted to determine the phase separation and morphology of the polyethylene modified binders. In all cases except the MA-grafted HDPE, the modified binders showed severe phase separation, which indicated a lack of compatibility between the polyethylene and asphalt binder used. The use of MA-grafted polyethylene produced remarkably better storage stability and microscopy results. This improvement was attributed to the following facts: the high polarity of MA-grafted polyethylene enhanced its solubility in asphalt binder, and the MA-grafted polyethylene had a greater tendency to interact with the carboxylic groups in asphalt binder, thus preventing the separation of the two individual phases. When comparing different MA-grafted polyethylene samples, HDPE showed the best storage stability results, followed by BHDPE, and LDPE, respectively. Additional rheological testing indicated that adding polyethylene generally increased the viscosity, stiffness, shear resistance, and deformation resistance of asphalt binder; these changes in binder properties were more pronounced for MA-grafted polyethylene as compared to commercial polyethylene.

"Use of Waste Products as Bitumen Modifiers in Costa Rica" by J.P. Aguiar-Moya, R.E. Villegas-Villegas, L.G. Loria-Salazar, and J. Salazar-Delgado in *EATA Conference Proceedings*, 2013.

Authors	J.P. Aguiar-Moya, R.E. Villegas-Villegas, L.G. Loria-Salazar, and J. Salazar-Delgado (Universidad de Costa Rica, Costa Rica)
Sponsor	Unknown
Plastic Type	Banana Bags, Styrofoam, Tire Rubber, and Car Bumper
Plastic Addition Method	Wet Process
Plastic Dosage	3% by Weight of Asphalt Binder for Banana Bags 3% by Weight of Asphalt Binder for Car Bumper 1.5% by Weight of Asphalt Binder for Styrofoam 3% by Weight of Asphalt Binder for Tire Rubber
Scope	Laboratory Binder Testing

This study evaluated the properties of asphalt binders modified with four waste plastics (i.e., banana bags, styrofoam, tire rubber, and automobile bumper) using the wet process, and compared them with two common asphalt binder modifiers: styrene-butadiene-styrene (SBS) and styrene-butadiene-rubber (SBR). AC-30 was the base asphalt binder used for modification. The waste plastic materials were added to the unmodified asphalt binder at different dosages ranging from 1.5% to 3.0% by weight of asphalt binder. The dosage of SBS and SBR was 2.5% by weight of asphalt binder. The thermogravimetric analysis (TGA) and differential scanning calorimeter (DSC) tests were conducted to characterize the thermal properties of waste plastic materials. Moreover, the Superpave asphalt binder tests and the multiple stress creep recovery (MSCR) test were conducted to characterize the rheological properties of asphalt binders with and without waste plastic modifiers. Atomic force microscopy (AFM) and Fourier transform infrared spectrometry (FTIR) were also conducted to analyze the topography and molecular structure of asphalt binders.

Test results indicated that polyethylene-based banana bags and automobile bumpers could be properly incorporated into asphalt binder due to their crystalline structures. However, tire rubber did not have homogeneous incorporation into the asphalt binder because of its amorphous nature. The TGA results indicated that all four waste plastic materials were not susceptible to thermal degradation at temperatures above 200°C; therefore, they would be suitable for asphalt binder modification. The MSCR test results indicated that the modified binders had less cumulative permanent deformation than the unmodified binder, indicating improved rutting resistance. Among the four waste plastic materials, banana bags yielded the least improvement in rutting resistance of the asphalt binder. The dynamic shear rheometer (DSR) $|G^*|\sin(\delta)$ results demonstrated that adding waste plastic materials (except banana bags) improved the fatigue resistance of the asphalt binder. Finally, results from AFM indicated that tire rubber remained as particulate materials in the asphalt binder, which suggested the necessity of using smaller-size tire rubber particles (passing sieve No. 50) for potential asphalt binder modification.

"Comparative Analysis of Conventional and Waste Polyethylene Modified Bituminous Mixes" by M.B. Khurshid, S. Ahmed, M. Irfan, and S. Mehmood in the *Proceedings of International Conference on Remote Sensing, Environment and Transportation Engineering*, 2013.

Authors	M.B. Khurshid, S. Ahmed, M. Irfan, and S. Mehmood (National University of Sciences and Technology, Pakistan)
Sponsor	Unknown
Plastic Type	Recycled High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: Up to 2 Percent by Weight of Asphalt Binder Dry Process: 4 to 14 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing, Cost Analysis

This study evaluated the use of recycled high-density polyethylene (HDPE) for asphalt mixture modification. HDPE was provided in shredded form with a particle size passing the 4.75 mm sieve (Figure 16). Both the dry process and wet process were explored. The base binder used for asphalt modification had an 80/100 penetration grade. For the wet process, up to 2.0 percent (by weight of asphalt binder) shredded HDPE was added to the asphalt binder at 160°C. However, this process could not produce homogenous binder blends with adequate storage stability and thus was excluded from further evaluation. For the dry process, shredded waste HDPE was added and mixed to coat the aggregates at 170°C, which was then mixed with the asphalt binder to produce HDPE modified mixtures. The dosage of waste HDPE added for binder replacement varied from 4 to 14 percent by weight of asphalt binder. Adding 8 percent waste HDPE yielded modified mixtures with the highest Marshall stability; thus, it was selected as the optimum HDPE dosage for mixture modification. The optimum HDPE modified mixture significantly outperformed the unmodified control mixture in the Hamburg wheel tracking test in terms of rutting resistance. A simplified cost analysis was conducted to determine the economic benefits of using waste HDPE for asphalt mixture modification. For constructing a 4-inch thick wearing course on a 12-foot wide lane, replacing 8 percent of asphalt binder by waste HDPE could reduce the materials cost by approximately Rupees 141,200 per lane-kilometer.

Figure 16. Shredded Waste HDPE Used for Asphalt Mixture Modification (Khurshid et al., 2013)

"Guidelines for the Use of Waste Plastic in Hot Bituminous Mixes (Dry Process) in Wearing Courses" by Indian Roads Congress at https://www.tce.edu/sites/default/files/PDF/IRC-Spec=Road-with-plastic-waste.pdf, 2013.

Authors	Indian Roads Congress, India
Sponsor	Unknown
Plastic Type	Recycled Low-density Polyethylene (LDPE), Recycled High-density Polyethylene (HDPE), Recycled Polyurethane (PU), Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	Up to 8 Percent by Weight of Asphalt Binder
Scope	Agency Specification

This document provides general guidelines for the use of waste plastic in the wearing course of asphalt pavements via the dry process. Existing laboratory and field performance studies in India have shown that using plastic-coated aggregates to produce asphalt mixtures provides significant engineering benefits, including higher resistance to deformation and water induced damage, increased durability and improved fatigue life, and improved stability and strength. The types of waste plastics allowed are limited to low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyurethane (PU), and polyethylene terephthalate (PET) only. The recommended dosage of waste plastic is 6 to 8 percent by weight of asphalt binder depending on the climatic conditions of high and low rainfall areas.

"Incorporation of Waste Plastic in Asphalt Binders to Improve their Performance in the Pavement" by L.M.B. Costa, H.M.R.D. Silva, J.R.M. Oliveira, and S.R.M. Fernandes in *International Journal of Pavement Research and Technology*, 2013.

Authors	L.M.B. Costa, H.M.R.D. Silva, J.R.M. Oliveira, and S.R.M. Fernandes (University of Minho, Portugal)
Sponsor	FEDER, FCT – Portuguese Foundation for Science and Technology
Plastic Type	Recycled High-density Polyethylene (HDPE), Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	5.0 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of waste plastics for asphalt modification via the wet process. Two types of waste plastics were tested: high-density polyethylene (HDPE) and low-density polyethylene (LDPE). Other non-plastic polymers evaluated in the study included virgin and recycled ethylene-vinyl acetate (EVA), virgin styrene-butadiene-styrene (SBS), recycled acrylonitrile–butadiene-styrene (ABS), and recycled crumb rubber (Figure 17). Each polymer was incorporated in two forms: powder form with a size below 0.45 mm and granulate form with a maximum size of 4.0 mm. The base binder used for polymer modification had a 35/50 penetration grade and a softening point of 52°C. A commercial elastomer modified binder, Styrelf, was also evaluated for performance comparison. For the preparation of modified binders, a low-shear mixer (350 rpm) was used to blend the polymer into asphalt binder for 1 hour at 180°C. The dosage of polymer was kept at 5.0 percent by weight of asphalt binder. Crumb rubber, ABS, and SBS did not digest completely in the asphalt binder in granulate form, resulting in non-homogenous binder blends. Adding polymer increased the softening point and reduced the penetration value of the base binder. The changes in these binder properties were more pronounced when HDPE, SBS, and EVA were used. All modified binders showed resilience values similar to or greater than that of Styrelf in the binder resilient test. Modified binders using SBS, EVA, and crumb rubber exhibited significant elastic recovery, while those modified with recycled HDPE, LDPE, and ABS presented negligible elastic recovery. In all cases, adding polymer increased the dynamic viscosity of the base binder. Binders modified with SBS had the highest viscosity, followed by EVA, HDPE and LDPE, crumb rubber, and then ABS, respectively. Finally, recommendations were provided towards mitigating the phase separation of polymer modified binders, including the use of a high-shear mixer, lowering the dosage of polymer, and adding compatibility additives such as polyphosphoric acid (PPA).

Figure 17. Different Types of Polymers Used for Asphalt Modification (Costa et al., 2013)

“Rutting Performance of Polyethylene, Lime and Elvaloy modified Asphalt Mixes” by K.M. Khan, Hanifullah, M. Afzal, F. Ali, A. Ahmed, and T. Sultan in *Life Science Journal*, 2013.

Authors	K.M. Khan, Hanifullah, M. Afzal, F. Ali, A. Ahmed (UET Taxila, Pakistan), T. Sultan (BZU Multan, Pakistan)
Sponsor	Unknown
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Dry Process
Plastic Dosage	19 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study aimed to evaluate the effectiveness of LDPE modified, lime modified and Elvaloy® modified asphalt mixtures in improving the rutting resistance of asphalt pavements. The study compared the performance of the aforementioned mixtures with a conventional agency-approved unmodified mixture as control. One unmodified asphalt binder with a 60/70 penetration grade and a polymer modified binder (PMB) containing 0.8 percent Elvaloy® were used. LDPE was evaluated as an additive to modify the properties of asphalt mixtures. Five different dosages of LDPE were tested: 5, 10, 15, 20, and 25 percent by weight of asphalt binder. Among all the dosages, 19 percent LDPE was selected as the optimum because at this dosage, the modified mixture had the smallest accumulated strain in a deformation test, and thus, was expected to have the best rutting resistance. Wheel-tracking test results showed that at 30°C, LDPE and lime modified mixtures had better rutting resistance than the unmodified and PMB mixtures. At 60°C, the LDPE modified mixture performed the best, followed by lime modified mixture, PMB mixture, and the unmodified control mixture, respectively. These results indicated that the use of LDPE, lime, and Elvaloy® modified binder had a positive effect on the rutting resistance of asphalt mixtures.

"Utilization of Waste Plastic Bottles in Asphalt Mixture" by T.B. Moghaddam, M.R. Karim, and M. Soltani in *Journal of Engineering Science and Technology*, 2013.

Authors	T.B. Moghaddam, M.R. Karim, and M. Soltani (University of Malaya, Malaysia)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	0.2 to 1 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study evaluated the use of waste plastic bottles in asphalt mixtures. The waste plastic sample used was obtained from waste polyethylene terephthalate (PET) bottles, which were smaller than 2.36 mm after cutting, crushing, and sieving. Different dosages of PET ranging from 0.2 to 1 percent by weight of aggregate were added to modify a stone mastic asphalt (SMA) mixture using the dry process. At each PET dosage, the optimum binder content of the SMA mixture was determined following the Marshall mix design procedure. It was found that the optimum binder content decreased as the PET dosage increased up to approximately 0.6 percent, while the opposite trend was observed at higher PET dosages. At 0.6 percent dosage, the modified SMA mixture had an optimum binder content of 6.29%, which was 0.48% lower than that of the unmodified control mixture. It was hypothesized that adding a low amount of PET would fill the voids in the SMA mixture and reduce the amount of asphalt binder needed to achieve the design air voids, while adding a high amount of PET would require more asphalt binder to coat the surface of the PET particles. The modified SMA mixtures at various PET dosages were also tested in the stiffness modulus and indirect tensile fatigue tests. Test results indicated that the stiffness of modified SMA mixtures increased as the PET dosage increased up to 0.2 percent but decreased at higher dosages. Adding PET was also found to significantly improve the fatigue life of the SMA mixtures, especially at higher PET dosages. This improvement in mixture fatigue resistance was attributed to the enhanced overall flexibility due to partial replacement of aggregates with PET.

"Crumb Tire Rubber and Polyethylene Mutually Stabilized in Asphalt by Screw Extrusion" by S. Wang, C. Yuan, and J. Deng in *Journal of Applied Polymer Science*, 2014.

Authors	S. Wang, C. Yuan (Shanghai Jiao Tong University, China), and J. Deng (Guangxi Key Lab of Road Structure and Materials, China)
Sponsor	National Natural Science Foundation of China, China
Plastic Type	High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	4.5, 7.5, 10.5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the effect of screw extrusion and use of maleic anhydride (MA)-based compatibilizer on the storage stability, morphology, and performance properties of asphalt binders modified with high-density polyethylene (HDPE) and crumb tire rubber (CTR) blends. HDPE was obtained from a commercial source with a specific gravity of 0.94. CTR was ground from truck tire rubber and then processed by dynamic devulcanization, which had acetone extraction of 19.3%, soluble rubber of 7.6%, gel content of 73.1%, and swelling ratio by toluene of 3.85. The base binder used for HDPE/CTR modification had a softening point of 45.3^{o}C and penetration of 70.1 (0.1 mm) at 25^{o}C. Linear low-density polyethylene (LLDPE) grafted with MA (LLDPE-g-MA) was evaluated as a potential compatibilizer to mitigate the phase separation of HDPE/CTR modified binders. For the preparation of modified binders, ternary HDPE/CTR/LLDPE-g-MA blends were first prepared by screw extrusion followed by pelletization. A high-shear mixer (4,000 rpm) was then used to blend the HDPE/CTR/LLDPE-g-MA blends into asphalt binder for 30 minutes at 180°C. The dosage of HDPE and CTR combined (at a 30:70, 50:50, or 70:30 ratio) was 15 percent by weight of asphalt binder. LLDPE-g-MA was added at 1, 3, and 5 percent by weight of HDPE and CTR.

The modified binders were first tested for penetration, softening point, ductility, and high-temperature storage stability. Test results showed that as the ratio of HDPE increased, the softening points of HDPE/CTR modified binders increased while the ductility and penetration values decreased. Although adding LLDPE-g-MA did not affect the physical properties of HDPE/CTR modified binders, it improved its storage stability by acting as a steric compatibilizer. This improvement was further confirmed through evaluating the morphological behavior of modified binders using an optical microscope, where the inclusion of LLDPE-g-MA enhanced the interfacial adhesion between spherical HDPE particles and irregular shaped CTR dispersed in the asphalt-rich phase. Thermal analysis using differential scanning calorimeter and Fourier transform infrared spectroscopy analysis confirmed the chemical interaction between anhydride maleic groups in LLDPE-g-MA and functional groups in asphalt binder. Figure 18 presents a hypothesized stabilization mechanism of HDPE/CTR/LLDPE-g-MA modified binders. Dynamic shear rheometer tests indicated that HDPE/CTR/LLDPE-g-MA modification improved the rutting resistance, thermal cracking resistance, temperature susceptibility, and elasticity of asphalt binders. Finally, it was concluded that HDPE and CTR could be successfully stabilized in asphalt binder through screw extrusion in the presence of compatibilizer.

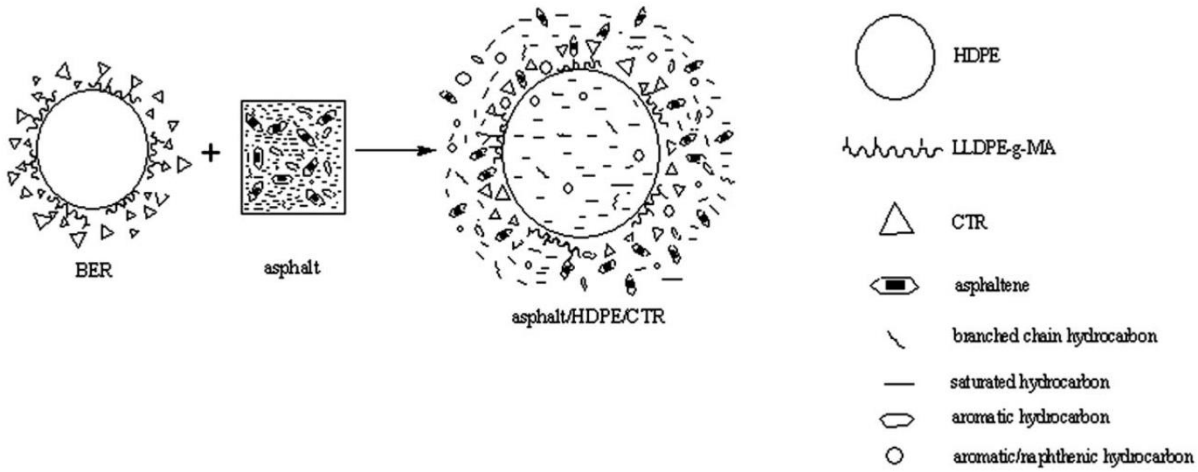


Figure 18. Hypothesized Stabilization Mechanism of HDPE/CTR/LLDPE-g-MA Modified Binders (Wang et al., 2014)

"Effect of Density of the Polyethylene Polymer on the Asphalt Mixtures" by N.Y. Ahmed and A.S.M. AL-Harbi in *Journal of Babylon University/Engineering Sciences*, 2014.

Authors	N.Y. Ahmed and A.S.M. AL-Harbi (Babylon University, Iraq)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2, 5, and 7 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the effect of the density of polyethylene (PE) polymer on the mechanical properties of asphalt mixtures. LDPE and HDPE were evaluated for asphalt modification via the wet process. As shown in Figure 19, LDPE and HDPE were provided in granule form, but their physical and chemical properties were not discussed. Each polymer was added at three different dosages of 2, 5, and 7 by weight of asphalt binder. The base binder used had a 40/50 penetration grade. Both LDPE and HDPE modified mixtures were prepared using the "drop-in" approach, and thus, had the same aggregate structure and optimum binder content as the unmodified control mixture. For performance evaluation, the Marshall stability test and wheel-tracking test were conducted. Test results showed that LDPE and HDPE modified mixtures had consistently higher Marshall stability values and lower rut depths than the unmodified control mixture, which indicated that use of LDPE and HDPE for asphalt modification had a positive effect on mixture stability and rutting resistance. The improvement in these mixture properties was more pronounced for HDPE than LDPE. Furthermore, for both LDPE and HDPE, adding 2 percent polymer yielded asphalt mixtures with the highest Marshall stability and lowest rut depth. Therefore, 2 percent was recommended as the optimum dosage of LDPE and HDPE for asphalt modification.

Figure 19. LDPE (Left) and HDPE (Right) Samples (Ahmed and AL-Harbi, 2014)

"Effect of High-Density Polyethylene on the Fatigue and Rutting Performance of Hot Mix Asphalt – A Laboratory Study" by F.M. Nejad, A. Azarhoosh, and G.H. Hamedi in *Road Materials and Pavement Design*, 2014.

Authors	F.M. Nejad, A. Azarhoosh, and G.H. Hamedi (Amirkabir University of Technology, Iran)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	5 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study investigated the potential use of high-density polyethylene (HDPE) for improving the rutting and fatigue characteristics of asphalt mixtures. The HDPE utilized was in powder form with all particles passing a #10 (2 mm) sieve and being retained on a #40 (0.42 mm) sieve. The specific gravity of HDPE was 0.97. The base binder used for HDPE modification had a 60/70 penetration grade. For preparation of modified binders, a high-shear mixer (3,000 rpm) was used to blend HDPE into the asphalt binder for 60 seconds at 185°C. The dosage of HDPE was 5 percent by weight of asphalt binder. Asphalt mixtures with and without HDPE modification were designed using the Marshall mix design procedure and characterized with the indirect tensile fatigue (IDF) and dynamic creep tests. Test results indicated that adding HDPE improved the fatigue and rutting resistance of asphalt mixtures at both dry and wet conditions. This improvement was mainly attributed to increased binder stiffness and improved bonding between the aggregate and asphalt binder after HDPE modification. Furthermore, the HDPE modified mixture was less susceptible to moisture conditioning than the unmodified control mixture, which indicated improved resistance to moisture damage.

“Effect of Using Polymers on Bituminous Mixtures Characteristics in Egypt” by A.M. Abd-Allah, M.I. El-sharkawi Attia, M.F. Abd-Elmaksoud Khamis, and E.M.Mohammed Deef-Allah in *IOSR Journal of Mechanical and Civil Engineering*, 2014.

Authors	A.M. Abd-Allah, M.I. El-sharkawi Attia, M.F. Abd-Elmaksoud Khamis, and E.M.Mohammed Deef-Allah (Zagazig University, Egypt)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE), Recycled Low-density Polyethylene (LDPE), Poly Vinyl Chloride (PVC)
Plastic Addition Method	Wet Process
Plastic Dosage	2 to 8 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study evaluated the effect of various types of polymers on the properties of asphalt binders and mixtures. A total of six polymers were tested, including poly vinyl chloride (PVC), phenol formaldehyde solid resin (PFSR), high-density polyethylene (HDPE), unsaturated polyester dissolved in styrene (UPdS), phenol formaldehyde liquid resin (PFLR), and recycled low-density polyethylene (LDPE) processed from waste plastic bags. The base binder used for polymer modification had a 60/70 penetration grade. Polymer modified binders were prepared following the wet process, where hand-mixing was used to blend the polymer into asphalt binder for six 10-minute periods at 160 to 170°C. Each polymer was added at different dosages ranging from 2 to 8 percent by weight of asphalt binder. In the first phase of the study, polymer modified binders were tested using the penetration and kinematic viscosity tests. Test results indicated that adding PVC, HDPE, PFSR, and recycled LDPE generally stiffened the asphalt binder by lowering its penetration and increasing viscosity, and that the stiffening effect was dependent upon the polymer dosage. However, the opposite trend was observed for UPdS and RFLR where the modified binders had consistently higher penetration and lower kinetic viscosity results than the base binder. The second phase of the study focused on determining the effect of PVC, HDPE, PFSR, and recycled LDPE on the Marshall stability and indirect tensile (IDT) strength of asphalt mixtures. For PVC and recycled LDPE, the Marshall stability of modified mixtures increased as the polymer dosage increased up to 4 percent, but then decreased at higher dosages. For HDPE and PFSR modified mixtures, the stability consistently increased as the polymer dosage increased. Adding polymers also improved the IDT strength of asphalt mixtures. The degree of improvement, however, was dependent upon the polymer dosage. For PVC, PFSR, and recycled LDPE, the optimum dosage rate was 4 percent by weight of asphalt binder, while the optimum dosage rate of HDPE was 5 percent. Based on the Marshall stability and IDT strength results, recycled LDPE was recommended as the most promising polymer for asphalt modification, followed by HDPE, PFSR, and PVC, respectively.

“Evaluation of Permanent Deformation Characteristics of Unmodified and Polyethylene Terephthalate Modified Asphalt Mixtures using Dynamic Creep Test” T.B. Moghaddam, M. Soltani, and M.R. Karim in *Materials and Design*, 2014.

“Estimation of the Rutting Performance of Polyethylene Terephthalate Modified Asphalt Mixtures by Adaptive Neuro-fuzzy Methodology” T.B. Moghaddam, M. Soltani, M.R. Karim, S. Shamshirband, D. Petkovic, and H. Baaj in *Construction and Building Materials*, 2015.

Authors	T.B. Moghaddam, M. Soltani, and M.R. Karim (University of Malaya, Malaysia)
Sponsor	Malaysian Ministry of Higher Education
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	0.2 to 1 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study evaluated the permanent deformation characteristics of unmodified and recycled polyethylene terephthalate (PET) modified stone mastic asphalt (SMA) mixtures using the dynamic creep test. The PET sample used was obtained from waste plastic bottles, which were washed, cut, and crushed, and then sieved into fractions with 100 percent passing the 2.36 mm sieve (Figure 20). PET was added at various dosages ranging from 0.2 to 1.0 percent by weight of aggregate. To prepare PET modified mixtures, preheated aggregates and asphalt binder were first mixed together, then mixed with PET added through the dry process. At each PET dosage, the optimum binder content of the SMA mixture was determined following the Marshall mix design procedure. The optimum binder content was found to decrease as the PET dosage increased up to approximately 0.6 percent, while the opposite trend was observed at higher PET dosages. At 0.6 percent dosage, the modified SMA mixture had an optimum binder content of 6.29%, which was 0.48% lower than that of the unmodified control mixture. The PET modified SMA mixtures were then tested using the dynamic creep test to evaluate their permanent deformation characteristics. The test was conducted at two stress levels (300 kPa and 400 kPa), and three test temperatures (10, 25, and 40°C). Test results indicated that PET modification had a significant impact on the permanent deformation characteristics of the SMA mixture; specifically, PET modified mixtures had improved rutting resistance compared to the unmodified control mixture as indicated by reduced cumulative permanent strain, increased number of load cycles at the primary and secondary deformation stages, and increased flow number values. This improvement in mixture rutting resistance due to PET modification was found more pronounced at higher PET dosages and higher stress levels.

Figure 20. Processing of Recycled PET Samples (Moghaddam et al., 2015)

“Experimental Characterization of Rutting Performance of Polyethylene Terephthalate Modified Asphalt Mixtures Under Static and Dynamic Loads” by T.B. Moghaddam, M. Soltani, and M.R. Karim in *Construction and Building Materials*, 2014.

Authors	T.B. Moghaddam, M. Soltani, M.R. Karim (University of Malaya, Malaysia)
Sponsor	University of Malaya Research Fund (Malaysia)
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	Up to 1 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study evaluated the rutting properties of PET modified asphalt mixtures under different loading conditions. An 80/100 penetration grade asphalt binder was selected. PET particles were obtained from post-consumer PET bottles. For preparing the PET particles, the plastic bottles were washed, dried, cut to small parts, and crushed. The crushed flakes were sieved and those passing the 2.36 mm sieve were used for mixture modification via the dry process. The dosage of PET varied from 0.1 to 1.0 percent by weight of aggregate. Results indicated that the bulk specific gravity and stiffness of the asphalt mixture increased at lower PET dosages (i.e., below 0.4 percent), and decreased at higher PET dosages. In comparison to the control mixture, the Marshall Quotient and indirect tensile strength results decreased with the addition of PET, which was possibly due to lower internal friction values of the compacted mix. The permanent deformation characteristics of unmodified and PET modified asphalt mixtures were evaluated under static and dynamic loading conditions. By establishing a relationship between cumulative permanent strain under static and dynamic loadings, the authors observed that: (a) PET modified mixtures with higher bulk specific gravity, Marshall Quotient, stiffness and tensile strength showed lower cumulative permanent strains under static loading; and (b) in case of the dynamic test, PET modified mixtures with lower specific gravity, Marshall Quotient, stiffness, and tensile strength showed lower cumulative permanent strain values. The authors highlighted that while adding PET might deteriorate the rutting performance of mixtures under static loading, this modifier could provide superior rutting performance under dynamic loadings. Finally, it was concluded that the common test methods used to evaluate the rutting susceptibility of asphalt mixtures, such as Marshall, stiffness and strength tests, were not appropriate to evaluate the rutting resistance of PET modified mixtures.

"An Approach to the Usage of Polyethylene Terephthalate (PET) Waste as Roadway Pavement Material" by M. Gürü, M.K. Cubuk, D. Arslan, S.A. Farzanian, and I. Bilici in *Journal of Hazardous Materials*, 2014.

Authors	M. Gürü, M.K. Cubuk, D. Arslan, S.A. Farzanian (Gazi University, Turkey), I. Bilici (Hitit University, Turkey)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Wet Process
Plastic Dosage	1, 2, 3, 5 and 10% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated two glycolyzed polyethylene terephthalate (PET) additives derived from waste plastic bottles [i.e., thin liquid polyol PET (TLPP) and viscous polyol PET (VPP)] for binder modification via the wet process and assessed their impacts on the performance properties of asphalt binders. The PET additives were added into the base binder at dosages ranging from 1% to 10% by weight of asphalt binder using a high-shear mixer. A wide range of laboratory binder tests were conducted to evaluate the physical and rheological properties of asphalt binders with and without PET modification. Moreover, the chemical properties of these binders were characterized using the scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR).

Test results indicated that adding TLPP and VPP reduced the viscosity and softening point but increased the penetration of the base binder. Adding VPP decreased binder ductility while adding TLPP did not show such an impact. The dynamic shear rheometer (DSR) and bending beam rheometer (BBR) results showed that adding TLPP and VPP reduced rutting resistance but improved the intermediate-temperature and low-temperature cracking resistance of the base binder due to the overall softening effect. The VPP modified binder outperformed the TLPP modified binder in terms of the DSR rutting resistance parameter. The study also indicated that mixing at 120°C for 10 minutes reduced the heat energy required to blend PET additives into the asphalt binder for polymer modification and reduced the aging of the resultant modified binders during the modification process.

“Effect of Waste Plastic Bottles on the Stiffness and Fatigue Properties of Modified Asphalt Mixes” by A. Modarres and H. Hamedi in *Journal of Materials and Design*, 2014.

Authors	A. Modarres and H. Hamedi (Babol Noshirvani University of Technology, Iran)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	2 to 10% by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the effect of polyethylene terephthalate (PET) on the stiffness and fatigue properties of asphalt mixtures at 5°C and 20°C. The study also compared the impacts of PET modification via the dry process versus styrene-butadiene-styrene (SBS) modification of the asphalt binder via the wet process. In this regard, crushed PET particles (Figure 21) were added into the aggregates at various dosages ranging from 2 to 10% by weight of asphalt binder before mixing with a 60/70 penetration grade binder. For comparison purposes, 5% SBS was added into the asphalt binder for polymer modification. The resilient modulus (Mr), fatigue, and indirect tensile strength (ITS) tests were performed to evaluate the stiffness and fatigue properties of PET modified versus SBS modified mixtures.

Test results indicated that although all the PET modified mixtures had acceptable Mr results, the mixture stiffness decreased as the PET dosage increased. On the other hand, adding PET enhanced the mixture fatigue resistance at both temperatures, but this improvement was not as pronounced as that due to SBS modification of the asphalt binder.

Figure 21. Crushed PET Particles (Modarres and Hamedi, 2014)

“Pavement Properties of Asphalt Modified with Packaging-Waste Polyethylene” by C. Fang, C. Wu, J. Hu, R. Yu, Z. Zhang, L. Nie, S. Zhou, and X. Mi in *Journal of Vinyl & Additive Technology,* 2014.

Authors	C. Fang, C. Wu, J. Hu, R. Yu, Z. Zhang, L. Nie, S. Zhou, X. Mi. (Xi’an University of Technology, People’s Republic of China)
Sponsor	National Natural Science Foundation of China
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	2, 4, 6, 8, and 10 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study investigated the use of waste PE retrieved from milk-packaging bags for asphalt modification via the wet process. The base binder used had a penetration grade of 42 (1/10 mm). The waste plastic was washed, dried, and cut into small pieces of 1.5 cm x 2.0 cm for ease of mixing with asphalt binder. For asphalt modification, waste PE was first added and mixed with asphalt binder for 2.5 hours at 180°C. The modified binder was then kept undisturbed for 30 minutes at 120°C followed by being high-speed sheared (3,600 rpm) for 1 hour at the same temperature. Laboratory binder tests showed that as the dosage of waste PE increased from 0 to 10 percent by weight of asphalt binder, the softening point of asphalt binder increased from 47°C to 81°C, while the penetration decreased from 42 (1/10 mm) to 15 (1/10 mm). The addition of waste PE also increased the Brookfield rotational viscosity of the asphalt binder at 120°C and 150°C. From the low-temperature anti-cracking test, it was observed that the use of waste PE for asphalt modification reduced the freeze-to-crack temperature and increased the freeze-to-crack stress of the asphalt mixture, which indicated improved low-temperature properties and possibly better cracking resistance. The wheel rutting test results indicated that the high-temperature stability and rutting resistance of the modified mixtures also improved as the dosage of waste PE increased. By analysis of infrared spectrums, the authors concluded that asphalt modification with the waste plastic utilized in this study was a physical process, because no change in the functional groups of asphalt binder was observed before and after the polymer incorporation. Therefore, the improvement in binder and mixture properties observed after asphalt modification was attributed to the swelling of waste plastic and its network structure within the asphalt binder.

“Preparation and Properties of Asphalt Modified with a Composite Composed of Waste Package Poly (vinyl chloride) and Organic Montmorillonite” by C. Fang, X. Liu, R. Yu, P. Liu, and W. Lei in *Journal of Materials Science & Technology*, 2014.

Authors	C. Fang, X. Liu, R. Yu, P. Liu, and W. Lei (Xi’an University, China)
Sponsor	National Natural Science Foundation of China, University of Ministry of Education of China, Local Service Program of Shaanxi Provincial Education Department
Plastic Type	Recycled Polyvinyl Chloride (PVC)
Plastic Addition Method	Wet Process
Plastic Dosage	6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the properties of asphalt binders modified with a composite composed of waste packaging polyvinyl chloride (WPVC) and organic montmorillonite (OMMT). WPVC/OMMT nanocomposites were prepared using a coextrusion process as illustrated in Figure 22. The base binder used for WPVC modification had a 90-penetration grade. WPVC and WPVC/OMMT modified binders were prepared using the wet process, where a high-shear mixer (3,750 rpm) was used to blend the polymers into asphalt binder for 1 hour at 150°C. After high-shear mixing, the modified binders were kept at 120°C for 30 minutes to ensure full swelling of WPVC and WPVC/OMMT. For all modified binders, the dosage of WPVC was kept at 6 percent by weight of asphalt binder. Fluorescence microscopy testing indicated that adding OMMT, due to its exfoliated structure, improved the compatibility between WPVC and asphalt binder and morphology of the resultant modified binders. WPVC modified binder was stiffer and more brittle than the base binder, as indicated by lower penetration and ductility values and a higher softening point. The addition of OMMT further increased the stiffness of the WPVC modified binder but improved its ductility. Furthermore, adding WPVC and OMMT reduced the temperature susceptibility of the base binder. Finally, WPVC and WPVC/OMMT modified binders had adequate storage stability with no phase separation observed.

Figure 22. Preparation of WPVC/OMMT Nanocomposites using a Coextrusion Process (Fang et al., 2014)

“Study of Strengthening of Recycled Asphalt Concrete by Plastic Aggregates” by B. Melbouci, S. Sadoun, and A. Bilek in *International Journal of Pavement Research and Technology*, 2014.

Authors	B. Melbouci, S. Sadoun, and A. Bilek (University of Tizi Ouzou, Algeria)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Dry Process
Plastic Dosage	2, 4, 6, and 8 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study aimed to evaluate the effectiveness of using plastic pellets as aggregates in asphalt mixtures. The objective was to control the arrangement of the skeleton of the granular mineral and select a mixture with adequate compactability. The asphalt binder selected in this study had a 35/50 penetration grade. The waste plastic utilized was granular polyethylene with particles size of 4 mm (Figure 23), which was obtained from cable phone plugs and plastic bottles (specific gravity of 0.910 to 0.965 and melting point of 140 to 150°C). For mixture modification, waste plastic was added by replacing 2, 4, 6, and 8 percent of aggregate. From the Marshall test, it was observed that adding waste plastic increased the Marshall stability values and decreased the flow values; as a result, asphalt mixtures containing waste plastic aggregate had higher Marshall quotient results, and thus, were excepted to have better deformation resistance than the unmodified control mixture. The addition of waste plastic aggregate also improved mixture compactability. Finally, compressive strength results measured by the Duriez Test showed that adding waste plastic aggregate increased the compressive strength of asphalt mixtures.

Figure 23. Waste Plastic Utilized in the Study (Melboci and Bilek, 2014)

"Sustainability Assessment of Bitumen with Polyethylene as Polymer" by T. Ali, N. Iqbal, M. Ali, and K. Shahzada in *IOSR Journal of Mechanical and Civil Engineering*, 2014.

Authors	T. Ali, N. Iqbal, M. Ali (The University of Lahore, Pakistan), and K. Shahzada (University of Engineering and Technology Peshawar, Pakistan)
Sponsor	Unknown
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	Up to 14 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of recycled low-density polyethylene (LDPE) for asphalt modification via the wet process. The LDPE sample was processed from waste plastic bags. The experimental design focused on comparing the penetration, softening point, and flash and fire points of LDPE modified versus unmodified binders. No information was provided for the type and grade of base binder used and the preparation of modified binders. Test results indicated that adding LDPE up to 14 percent by weight of asphalt binder reduced penetration but increased softening point of the base binder, which was expected to yield asphalt mixtures with increased stiffness and improved rutting resistance. LDPE modified binders also had higher flash point and fire point than the unmodified binder.

“Installation and Laboratory Evaluation of Alternatives to Conventional Polymer Modification for Asphalt” by S.D. Diefenderfer and K.K. McGhee as *Virginia Center for Transportation & Research Final Report VCTIR 15-R15*, 2015.

Authors	S.D. Diefenderfer and K.K. McGhee (Virginia Center for Transportation Innovation and Research)
Sponsor	Virginia Department of Transportation
Plastic Type	Styrene Butadiene Styrene-Polyethylene (SBS-PE) Copolymer from Honeywell
Plastic Addition Method	Wet Process
Plastic Dosage	Not Specified
Scope	Laboratory Binder Testing, Field Project

This study investigated the suitability of styrene butadiene styrene-polyethylene (SBS-PE) copolymer and ground tire rubber (GTR) modified binders for use in Virginia. The research approach undertaken was a traditional head-to-head field demonstration project of surface layer replacement for a 3.5-mile pavement. Three field sections were constructed; one using a conventional SBS modified binder as control and the other two using alternative SBS-PE and GTR modified binders. The SBS-PE copolymer was supplied by Honeywell (https://www.honeywell.com/). The SBS-PE modified binder was formulated at an asphalt terminal by Nustar; however, the dosage of SBS and PE polymers used was not provided. All mixtures had a nominal maximum aggregate size of 12.5 mm and 30 percent recycled asphalt pavement (RAP) and were produced as warm mix asphalt using a foaming system. During construction, raw materials and plant mixes were sampled for laboratory testing, including performance grading, multiple stress creep recovery (MSCR), dynamic modulus (E*) test, flow number (FN) test, asphalt pavement analyzer (APA), bending beam fatigue (BBF) test, overlay test (OT), and tensile strength ratio (TSR) test. Binder results showed that both the control SBS modified and SBS-PE modified binders met the PG 76-22 and PG 64E-22 requirements per AASHTO M 320 and AASHTO MP 19, respectively. These results indicated that the SBS-PE copolymer provided sufficient modification as an acceptable elastomeric polymer. From the mixture E* test, the SBS-PE modified mixture had slightly higher stiffness and thus was expected to be more rutting resistant than the control SBS modified mixture. This increase in mixture stiffness, however, resulted in a reduced fatigue life in the BBF test. No significant difference in the APA or OT test results was observed between the two mixtures. Despite the high dry and wet tensile strengths, the SBS-PE modified mixture failed to meet the agency’s TSR requirement, indicating a potential for moisture damage. Based on these results, the performance of the SBS-PE modified mixture was considered equivalent to the control SBS modified mixture. Therefore, a recommendation was provided for the Virginia Department of Transportation to continue to allow the use of SBS-PE modified binders as an alternative to SBS modified binders.

"Stiffness Modulus of Polyethylene Terephthalate Modified Asphalt Mixture: A Statistical Analysis of the Laboratory Testing Results" by T.B. Moghaddam, M. Soltani, M.R. Karim in *Materials and Design*, 2015.

Authors	T.B. Moghaddam, M. Soltani, M.R. Karim (University of Malaya, Malaysia)
Sponsor	Ministry of Higher Education, Malaysia
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	0.5 and 1 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study evaluated the effects of applied stress and temperature on the stiffness modulus of unmodified and PET modified asphalt mixtures using Response Surface Methodology (RSM). Asphalt mixtures were produced with an 80/100 penetration grade asphalt binder and granite aggregate. PET particles were obtained from post-consumer PET bottles. For preparing the PET particles, the plastic bottles were washed, dried, cut to small parts, and crushed. The crushed flakes were sieved and those passing the 2.36 mm sieve were used for mixture modification. PET was added at two dosages of 0.5 and 1.0 percent by weight of aggregate. Both unmodified and PET modified mixtures were designed using the Marshall mix design process. The resultant optimum binder content of the unmodified control mixture was 6.8 percent, which was 0.4 and 0.3 percent higher than the modified mixtures containing 0.5 percent and 1 percent PET, respectively. The indirect tensile stiffness modulus (ITSM) test results showed that the stiffness of asphalt mixtures was dependent upon the applied stress level and PET dosage, with the stiffness decreasing as the PET dosage increased. It was also observed that the overall mixture stiffness became more susceptible to temperature variations after the addition of PET. Moreover, the impact of adding PET on mixture stiffness was found more pronounced at lower temperatures. Finally, as compared to applied stress level, PET dosage showed a more significant effect on the stiffness modulus of asphalt mixtures.

“Storage Stability and Rheological Properties of Asphalt Modified with Waste Packaging Polyethylene and Organic Montmorillonite” by R. Yu, C. Fang, P. Liu, X. Liu, and Y. Li in *Applied Clay Science*, 2015.

Authors	R. Yu, C. Fang, P. Liu, X. Liu, and Y. Li (Xi'an University of Technology, China)
Sponsor	Natural Science Foundation of China, Program for New Century Excellent Talents in University of Ministry of Education of China, Local Service Program of Shaanxi Provincial Education Department, China
Plastic Type	Blend of Recycled Linear Low-density Polyethylene (LLDPE) and Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	4 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the storage stability and rheological properties of asphalt binders modified with waste packaging polyethylene (WPE) and organic montmorillonite (OMt). The base binder used had 86.1 dmm penetration value, 51.2ºC softening point, 111.7 cm ductility, and 0.45 Pa.s viscosity. WPE was obtained from recycled waste milk bags, washed, dried, and then extruded into particles for asphalt modification. WPE was mainly composed of linear low-density polyethylene (LLDPE) and low-density polyethylene (LDPE). The nanosized OMt used was provided in powder form with creamy white color. A high-shear mixer (3,750 rpm) was used to blend WPE and OMt into asphalt binder for 1.5 hours at 150°C. During the mixing process, the modified binders were left quiescent for 10 minutes after being blended for every 30 minutes to ensure full swelling of the additives. The dosage of WPE was 4 percent by weight of asphalt binder. OMt was added at various dosages ranging from 0.3 to 1.2 percent by weight of asphalt binder. It was found that adding low contents of OMt improved the storage stability of WPE modified binders, while further increasing the OMt content did not have any positive effect. The fluorescence microscopic images indicated that the improvement in storage stability at low OMt contents was due to the exfoliation of OMt during shearing, which improved the orientation of WPE microfibers and its distribution within the asphalt binder. Adding OMt also increased the penetration, ductility, and viscosity of WPE modified binder but had no impact on its softening point. Through the evaluation of rheological properties, modified binders containing WPE and OMt were expected to have superior high-temperature rutting resistance. Finally, scanning electron microscopy images indicated that adding OMt, due to its exfoliated layer structure, could enhance the low-temperature rheological properties and cracking resistance of asphalt binders.

“Asphalt Design using Recycled Plastic and Crumb-rubber Waste for Sustainable Pavement Construction” by I.M. Khan, S. Kabir, M.A. Alhussain, and F.F. Almansoor in the *International Conference on Sustainable Design, Engineering and Construction*, 2016.

Authors	I.M. Khan, S. Kabir, M.A. Alhussain, and F.F. Almansoor (King Faisal University, Saudi Arabia)
Sponsor	Unknown
Plastic Type	Recycled High-density Polyethylene (HDPE), Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2, 4, 8, and 10 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) for asphalt modification using the wet process. A PG 64-10 base binder from a local Saudi refinery was modified with 2, 4, 8, and 10 percent LDPE and HDPE by weight of asphalt binder. The modified binders were prepared by mixing the base binder and LDPE or HDPE for 2 hours at 165°C; however, the type of mixer used was not discussed. The modified binders were tested in a dynamic shear rheometer to characterize their rheological properties at multiple temperatures ranging from 46 to 70°C. Test results indicated that adding LDPE and HDPE improved the elastic behavior and rutting resistance of the base binder, as indicated by a decrease in the phase angle (δ) and an increase in the Superpave binder rutting parameter ($|G^*|/\sin(\delta)$). The addition of 10 percent LDPE and 4 percent HDPE yielded the best rutting resistance; thus, these were selected as the optimum dosages for asphalt modification.

"A Comparative Study of Bituminous Mixtures with Recycled PE Added by Dry and Wet Processes" by S. Angelone, F. Martinez, and M.C. Casaux in *RILEM*, 2016.

Authors	S. Angelone, F. Martinez, and M.C. Casaux (University of Rosario, Argentina)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene from Silo Bags
Plastic Addition Method	Dry Process, Wet Process
Plastic Dosage	Dry Process: 2, 4, and 6% by Weight of Asphalt Mixture Wet Process: 2 and 3% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

"Silo bags" are large plastic bags with three layers of polyethylene used for storage of agricultural grains. Although the silo bags can be reused several times, eventually they are damaged at which time they are typically landfilled as waste. Thus, there is interest in the possibility of using this waste polyethylene as an additive for asphalt mixtures. This research investigated the effects of recycled polyethylene (RP) from silo bags on the properties of asphalt mixtures. The RP from silo bags were dried and chopped with a maximum size between 6 mm and 10 mm. Both the dry (added to the aggregates) and wet (added to the asphalt binder) addition methods were applied for the laboratory tests. Different dosages of RP, including 2, 4, and 6% (by weight of asphalt mixture) for the dry method, as well as 2 and 3% (by weight of asphalt binder) for the wet process were used in this study.

For the wet process, adding RP decreased the penetration and increased the softening point, rotational viscosity, and elastic recovery of the asphalt binder. Asphalt mixtures were designed according to the Marshall method. All the mixtures had an optimum asphalt content of 4.9%. A styrene-butadiene-styrene (SBS) modified mixture was included as a comparative mixture. Average volumetric properties were measured, and various mechanical properties of asphalt mixtures were evaluated using the Marshall stability and flow, indirect tensile strength (ITS), moisture susceptibility, Dynamic Modulus, and wheel tracking (EN-12697-22) tests. Test results indicated that the wet process of adding RP resulted in lower Marshall stability and greater flow of the asphalt mixture, while for the dry process, adding RP increased the mixture's Marshall stability and flow. Additionally, ITS decreased as the percentage of RP increased for both addition methods, but the tensile strength ratio (TSR) results were acceptable. Adding RP decreased the dynamic modulus values of the asphalt mixture at low temperature and high frequency, but the opposite trend was observed for the results at high temperature and low frequency. Finally, the RP modified mixtures had significantly lower rut depth in the wheel tracking test than the control mixture, indicating improved rutting resistance.

"Irradiated Recycled High Density Polyethylene Usage as a Modifier for Bitumen" by P. Ahmedzade, T. Günay, O. Grigoryeva, and O. Starostenko in Journal of Materials in Civil Engineering, 2016

Authors	P. Ahmedzade, T. Günay (Ege University, Turkey), O. Grigoryeva, and O. Starostenko (Institute of Macromolecular Chemistry of the National Academy of Sciences of Ukraine, Ukraine)
Sponsor	Unknown
Plastic Type	Recycled High-density Polyethylene
Plastic Addition Method	Wet Process
Plastic Dosage	1, 3, 5, 7, and 9% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the impact of electron beam irradiation on the chemical structure of recycled high-density Polyethylene (HDPE) and characterized the physical and rheological properties of asphalt binders modified with irradiated HDPE. A 160/220 penetration grade asphalt binder was used, and different dosages of electron beam irradiated recycled HDPE (1, 3, 5, 7, and 9% by weight of asphalt binder) were added to the asphalt binder for modification utilizing the wet process. Various tests including Fourier transform infrared spectrometry (FTIR), differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), dynamic shear rheometer (DSR), and bending beam rheometer (BBR) were conducted on the irradiated HDPE samples and the resultant modified binders. FTIR spectroscopy was conducted to determine the effect of irradiation on the chemical structure of HDPE and the molecular structure of the modified binders. DSC and TGA were used to evaluate the thermal properties of irradiated HDPE and asphalt binders with and without HDPE modification. Conventional asphalt binder tests such as the penetration, ductility, softening point, and viscosity tests were conducted on the modified and unmodified binders. Additionally, these asphalt binders were subjected to rolling thin-film oven (RFTO) and pressure aging vessel (PAV) and tested for weight loss and rheological properties over a wide temperature range.

The FTIR and DSC analysis results indicated that the chemical interaction between irrigated HDPE and asphalt binder improved their chemical bonding, and that irrigated HDPE modification improved the asphalt binder's resistance against thermal degradation in comparison with modification using non-irradiated HDPE. The morphology analysis confirmed the FTIR analysis results and highlighted that irrigated HDPE dispersed well in the asphalt binder. The conventional asphalt binder test results indicated a stiffening effect from irrigated HDPE modification. Furthermore, the irrigated HDPE modified binders exhibited reduced susceptibility to RTFO aging, reduced temperature susceptibility, and improved high-temperature properties than the unmodified binder. Adding irrigated HDPE did not have a remarkable effect on the low temperature properties of the asphalt binder. Finally, this study suggested using irrigated HDPE modified binders in regions with warm climates and limiting using more than 3% irrigated HDPE for binder modification in cold climate regions to prevent potential thermal cracking issues.

“Comparative Analysis of the Performance of Asphalt Concretes Modified by Dry Way with Polymeric Waste” by P. Lastra-González, M.A. Calzada-Pérez, D. Castro-Fresno, Á. Vega-Zamanillo in *Construction and Building Materials*, 2016.

Authors	P. Lastra-González, M.A. Calzada-Pérez, D. Castro-Fresno, Á. Vega-Zamanillo (Universidad de Cantabria, Spain)
Sponsor	European Union
Plastic Type	Recycled Polyethylene (PE), Recycled Polypropylene (PP), Recycled Polystyrene (PS)
Plastic Addition Method	Dry Process
Plastic Dosage	1 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study evaluated the use of polymeric waste for asphalt mixture modification via the dry process. Four polymeric waste samples were tested, including polyethylene (PE) from micronized containers, polypropylene (PP) from ground caps, polystyrene (PS) from hangers, and rubber from end-of-life tires (ELT). As shown in Figure 24, PE, PP, and PS were provided in shredded or granulate form with a particle size ranging from 2 to 6 mm, while ELT was provided in powder form with a maximum particle size of 1 mm. Polymer wastes were added as direct replacement of aggregate filler and its dosage used was 1.0 percent by weight of aggregate. For the preparation of modified mixtures, polymeric waste was added to the hot aggregates, which were then mixed with asphalt binder. All modified mixtures were designed using the “drop-in” approach, and thus, had the same aggregate structure and optimum binder content as the unmodified control mixture. Both modified and control mixtures were tested using the wheel tracking test, four-point bending test, and workability test. Test results indicated that the addition of all polymer wastes increased the mixture stiffness, especially when PE, PP, and ELT were used. However, polymer waste modified mixtures showed no improvement in fatigue resistance as compared to the control mixture. Adding PE, PP, and ELT improved the mixture’s resistance to permeant deformation, while the opposite trend was observed for PS. This improvement from PE and PP modification was mainly attributed to the increased internal resistance of the mineral aggregate skeleton and improved mixture cohesion. There was no significant difference in the workability of the control versus polymeric waste modified mixtures. Based on these results, the use of PE, PP, and ELT was recommended for asphalt mixture modification.

Figure 24. Polymeric Waste Samples Used for Asphalt Mixture Modification (From Left to Right: PE, PP, PS, and ELT) (Lastra-González et al., 2016)

"Formulation and Processing of Recycled-low-density-polyethylene-modified Bitumen Emulsions for Reduced-temperature Asphalt Technologies" by A.A. Cuadri, C. Roman, M. García-Morales, F. Guisado, E. Moreno, and P. Partal in *Chemical Engineering Science*, 2016.

Authors	A.A. Cuadri, C. Roman, M. García-Morales (Universidad de Huelva, Spain), F. Guisado, E. Moreno (Centro de Tecnología Repsol, Spain), and P. Partal (Universidad de Huelva, Spain)
Sponsor	MINECO-FEDER (Subprogram INNPACTO project IPT-2012-0316-370000)
Plastic Type	Blend of Recycled Low-density Polyethylene (LDPE) and Recycled Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Asphalt-Plastic Emulsion
Plastic Dosage	2 to 5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of an inline emulsification procedure to formulate and process storage-stable asphalt emulsions modified with recycled low-density polyethylene and linear low-density polyethylene (LDPE/LLDPE) blend. The LDPE/LLDPE blend was obtained from an industrial source and had a degree of crystallinity of 28 percent. Two base binders were used for LDPE/LLDPE modification: one had a penetration grade of 160/220 and the other 70/100. An (alkyl)trimethylenediamine derived from N-tallow was used as an emulsifier for the preparation of cationic LDPE/LLDPE modified asphalt emulsions. For the preparation of asphalt emulsions, a high-shear mixer (5,000 rpm) was first used to blend LDPE/LLDPE into asphalt binder for 1 hour at 170°C. The dosage of LDPE/LLDPE varied from 2 to 5 percent by weight of asphalt binder. Then, the emulsion aqueous phase was prepared by dispersing 2.5 percent emulsifier into distilled water at pH 1, with a four-bladed turbine rotating at 500 rpm for 5 hours at 60°C. Finally, an in-line emulsification process was used to produce LDPE/LLDPE modified asphalt emulsions at high temperature and pressure. LDPE/LLDPE modified binders were characterized through optical imaging, differential scanning calorimetry (DSC), viscous flow measurements, and high-temperature storage stability. Test results indicated that adding LDPE/LLDPE above 3 percent by weight of asphalt binder significantly increased the softening points but reduced the penetration values of the two base binders. The viscosity of asphalt binders also increased after LDPE/LLDPE modification, alongside the development of an apparent non-Newtonian behavior. Phase separation was observed in LDPE/LLDPE modified binders within the first few hours of high-temperature storage without agitation, while LDPE/LLDPE modified asphalt emulsions showed adequate storage stability for at least seven days based on visual observation. The asphalt emulsions exhibited broad droplet size distributions and non-Newtonian viscous flow behavior. Optical microscopy and DSC showed that as compared to LDPE/LLDPE modified binders, asphalt emulsion residues had enhanced modification with increased dispersion of the swollen polymer phase in asphalt binder, which contributed to the enhanced compatibility and storage stability.

"Green Pavements: Reuse of Plastic Waste in Asphalt Mixtures" by S. Angelone, M.C. Casaux, M. Borghi, and F.O. Martinez in *Materials and Structures*, 2016.

Authors	S. Angelone, M.C. Casaux, M. Borghi, and F.O. Martinez (National University of Rosario, Argentina)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE), Recycled Polypropylene (PP)
Plastic Addition Method	Dry Process
Plastic Dosage	2, 4, and 6 Percent by Weight of Asphalt Mixture
Scope	Laboratory Mixture Testing

This study evaluated the use of plastics waste for asphalt mixture modification via the dry process. Three plastic waste samples were tested, including two polyethylene (PE) obtained through processing of farm-use silo bags (one in flake form and the other in pellet form) and one polypropylene (PP) in chip form, as shown in Figure 25. For the preparation of plastic modified mixes, PE and PP were added directly into the aggregates and filler, which were then mixed with the asphalt binder at 160°C. For each plastic sample, modified mixtures were prepared at three dosages of 2, 4, and 6 percent by weight of asphalt mixture, except that the flake PE was added using the "direct addition" method while the pellet PE and PP were added using the "aggregate replacement" method. All PE and PP modified mixtures were prepared using the "drop-in" approach and thus had the same binder content as the control mix. Volumetric analyses indicated that in most cases, PE and PP modified mixtures had lower density and higher air voids than the control mixture. Adding PE in both forms increased the Marshall stability and flow of the control mixture, while the opposite trend was observed for the addition of PP. Based on the Marshall Quotient results, PE modified mixtures were expected to have comparable permanent deformation resistance as the control mixture, which outperformed the PP modified mixtures. The three plastic samples showed considerably different impacts on the indirect tensile (IDT) test results: adding flake PE reduced the IDT strength but increased the fracture energy; adding pellet PE increased the fracture energy but had no impact on the IDT strength; and finally, adding PP increased the IDT strength but reduced the fracture energy. The addition of PE or PP did not affect the moisture susceptibility of the control mixture in the tensile strength ratio (TSR) test. Adding PE improved the mixture stiffness-temperature characteristics; the modified mixtures had higher dynamic modulus (E*) values at high temperatures but lower E* values at low temperatures, which could provide better resistance to permanent deformation and thermal cracking. Finally, PE and PP modified mixtures outperformed the control mixture in terms of rutting resistance in both the wheel tracking and creep compliance tests.

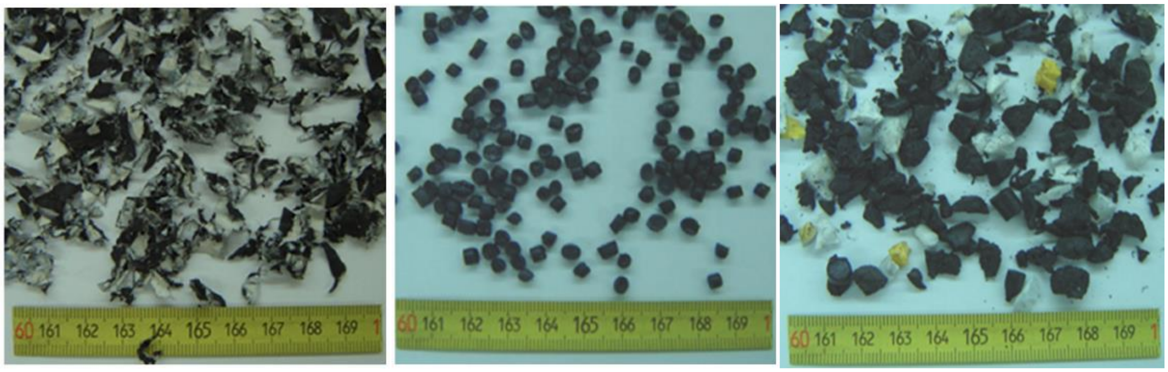


Figure 25. Waste Plastic Samples (From Left to Right: Flake PE, Pellet PE, and Chip PP) (Angelone et al., 2016)

“Modification of Asphalt Binders by Polyethylene-type Polymers” by D. Brożyna and K.J. Kowalski in *Journal of Building Chemistry*, 2016.

Authors	D. Brożyna and K.J. Kowalski (Warsaw University of Technology, Poland)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE), Low-density Polyethylene (LDPE), Linear Low-density Polyethylene (LLDPE), Ethylene/Butyl Acrylate (EBA) Copolymer, Ethylene/Butyl Acrylate/Maleic Anhydride (EBM) Terpolymer
Plastic Addition Method	Wet Process
Plastic Dosage	5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of polyethylene (PE)-based polymers for asphalt modification via the wet process. Five different types of PE-based polymers were tested, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), ethylene/butyl acrylate (EBA) copolymer, ethylene/butyl acrylate/maleic anhydride (EBM) terpolymer. The base binder used for PE modification had a 50/70 penetration grade. For the preparation of PE modified binders, a high-shear mixer (4,000 rpm) was used to blend the polymer into asphalt binder for 3 hours at 180°C. The PE polymer dosage was kept constant at 5 percent by weight of asphalt binder. After modification, the binders were tested for penetration, softening temperature, and elastic recovery, before and after aging using the Rolling Thin Film Oven (RTFO) test. Test results indicated that adding PE-based polymers reduced the penetration but increased the softening point of the base binder, which indicated the binder stiffening effect. Among all the polymers tested, only EBM terpolymer improved binder elasticity, while asphalt binders modified with the other PE-based polymers had either similar or reduced elastic recovery results as compared to the base binder.

“Recycling of Polyethylene Terephthalate (PET) Plastic Bottle Wastes in Bituminous Asphaltic Concrete” by A.O. Sojobi, S.E. Nwobodo, and O.J. Aladegboye in *Cogent Engineering*, 2016.

Authors	A.O. Sojobi, S.E. Nwobodo, and O.J. Aladegboye (Landmark University, Nigeria)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: 5 to 20 Percent by Weight of Asphalt Binder Dry Process: 10 to 30 Percent by Weight of Aggregate
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study evaluated the impact of polyethylene terephthalate (PET) plastic bottle wastes on the performance properties of asphalt binders and mixtures. Both the dry process and wet process were explored. In the dry process, PET waste was added into the coarse aggregates at a temperature ranging from 160 to 180°C to form plastic-coated aggregates (PCA), which were then mixed with fine aggregates, mineral fillers, and asphalt binder; the resultant mixture was referred to as PCA mixture. In the wet process, PET waste was added as asphalt binder replacement. The standard mixing procedure was followed to mix aggregates, mineral fillers, and asphalt binder, which was then mixed with shredded PET waste at approximately 170°C; the resultant mixture produced using this process was referred to as plastic modified binder (PMB) mixture. The dosage of PET waste used for the dry process varied from 10 to 30 percent by weight of aggregate, while the dosage used for the wet process varied from 5 to 20 percent by weight of asphalt binder. The base binder used had a 60/70 penetration grade. Both PCA and PMB mixtures were designed following the Marshall mix design procedure. Laboratory binder tests indicated that adding PET waste decreased the penetration value but increased the softening point and ductility values of the base binder; additionally, the changes in these binder properties were more significant at higher polymer dosages. Both PCA and PMB mixtures at their optimum PET and asphalt binder contents had higher Marshall stability than the control unmodified mixture, which was indicative of improved mixture stiffness and rutting resistance. As compared to PMB mixtures, PCA mixtures allowed the use of more PET waste for asphalt mixture modification.

“Reinforcement of Asphalt Concrete Mixture using Recycle Polyethylene Terephthalate Fiber” by N. Usman, M.I.B.M. Masirin, K.A. Ahmad and A.A. Wurochekke in *Indian Journal of Science and Technology*, 2016.

Authors	N. Usman, M.I.B.M. Masirin, K.A. Ahmad and A.A. Wurochekke (Universiti Tun Hussein Onn Malaysia, Malaysia)
Sponsor	University Tun Hussein Onn Malaysia, Malaysia
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	0.3, 0.5, 0.7 and 1 Percent by Weight of Asphalt Mixture
Scope	Laboratory Mixture Testing

The present study investigated the reinforcement effect of PET fiber on the strength of asphalt mixtures. The PET particles were obtained from post-consumer PET bottles. For preparing the PET particles, the plastic bottles were washed, dried, cut in sheets, and then shredded to 0.4 mm x 10 mm particle sizes (Figure 26). The PET fiber was blended into the mixture using the dry process. Three different dosages of PET fiber were evaluated: 0.3, 0.5, 0.7 and 1 percent by weight of asphalt mixture. The control asphalt mixture contained the asphalt binder with a penetration of 83 (1/10 mm) at 25°C and softening point of 43°C and had an optimum binder content of 6 percent. Response surface methodology (RSM) was used in the analysis of data obtained in this study. Using Design Expert 7.0 software, two factors (PET fiber dosage and temperature) and one response (resilient modulus) were analyzed at 30 runs using historic data. To estimate the response variable, a Montgomery quadratic polynomial regression model was used for four independent variables. The model was checked by means of analysis of variance (ANOVA). Resilient modulus test results indicated that adding PET fiber increased mixture stiffness. Furthermore, temperature and PET fiber dosage showed a significant impact on the resilient modulus results; specifically, resilient modulus increased with the increase of PET fiber dosage and decreased with an increase of temperature. The improvement of resilient modulus in PET reinforced asphalt mixtures was more significant at lower temperatures than at higher temperatures. Finally, the optimum PET fiber content was found at 0.7 percent by weight of asphalt mixture.

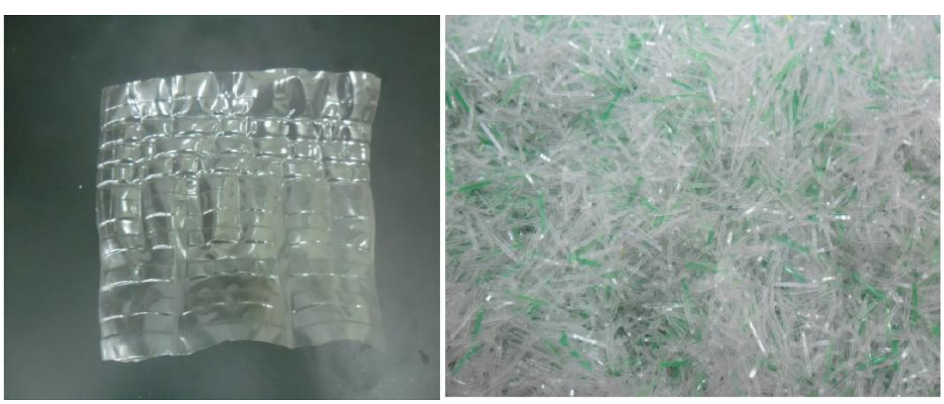


Figure 26. Recycled PET Sheet (Left) and Fiber (Right) (Usman et al., 2016)

"A Study on the Plastic Waste Treatment Methods for Road Construction" by R. Bajpai, M.A. Khan, O.B. Sami, P.K. Yadav, and P.K. Srivastava in *International Journal of Advance Research, Ideas and Innovations in Technology*, 2017.

Authors	R. Bajpai, M.A. Khan, O.B. Sami, P.K. Yadav, and P.K. Srivastava (Azad Institute of Engineering and Technology, India)
Sponsor	Unknown
Plastic Type	Polypropylene (PP)
Plastic Addition Method	Dry Process
Plastic Dosage	Not Specified
Scope	Laboratory Mixture Testing

This study evaluated the feasibility of recycling plastics waste in road construction. First, different types and classifications of plastic wastes, details of shredding and blending of plastic wastes, mix design approaches, and requirements on the physical properties of aggregates and asphalt binders for pavement construction were reviewed. The main findings are summarized as follows: (1) Plastic wastes can be commonly divided into high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP). Polyethylene (PE) is generally available in the form of plastic bags and PP is available in the form of plastic bottles and mat sheets; (2) Shredding refers to the process of cutting plastics into small sizes between 2.36mm to 4.75mm. An agglomerator can be used to shred thin films of PE and PP carry bags; (3) For preparation of plastic modified binders, the cut and sieved pieces of plastics are typically added to the asphalt binder and blended using a mechanical stirrer for 30 minutes at 170 to 180°C; (4) Separation testing is commonly used to characterize the homogeneity of plastic modified binders; and (5) In addition to the wet process, plastic can also be added to the aggregates through the dry process. The dry process can be executed in a hot mix plant, mini hot mix plant, and central mixing plant. Asphalt mixtures prepared with plastic-coated aggregates claim to perform better than those prepared with plastic modified binders in many perspectives.

Laboratory testing was then conducted to evaluate the physical properties of aggregates coated with two different types of PP: PP8 and PP 10. Table 8 summarizes the test results. As shown, PP coating improved the impact resistance, crushing resistance, stripping resistance, and abrasion resistance of aggregates. PP-coated aggregates also had higher specific gravity and reduced water absorption than the uncoated control aggregates.

Table 8. Aggregate Test Results of Polypropylene-coated versus Uncontacted Aggregates (Bajpai et al., 2017)

	Moisture Absorption (%)	Aggregate Impact Value (%)	Aggregate Crushing Value (%)	Los Angeles Abrasion Value (%)	Specific Gravity	Stripping Value (%)
Control	1.7	5.43	19.2	13.42	2.45	8
PP8	Nil	4.91	13.3	10.74	2.70	Nil
PP10	Nil	4.26	9.8	9.41	2.85	Nil

"Properties of Asphalt Binder and Asphalt Concrete Containing Waste Polyethylene" by P. Singh, A. Tophel, and A.K. Swamy in *Journal of Petroleum Science and Technology*, 2017.

Authors	P. Singh, A. Tophel, and A.K. Swamy (Indian Institute of Technology Delhi, India)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene
Plastic Addition Method	Dry Process
Plastic Dosage	2, 4, and 6% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study evaluated the properties of asphalt binders and mixtures modified with waste polyethylene (PE). For mixture preparation, 2, 4, and 6% waste polyethylene (by weight of asphalt binder) was added directly to the hot aggregates and then mixed with the asphalt binder. The Marshall samples were tested for volumetric properties, Marshall stability, and flow. Additionally, the mixture samples were aged for 4, 24, and 48 hours at 135°C to simulate short-term, medium-term, and long-term aging, respectively. Asphalt binders were then extracted from the mixtures at different aging conditions and subjected to dynamic shear rheometer (DSR) testing over a range of temperature and frequency.

The mixture test results showed that the Marshall stability first increased and then decreased as the polyethylene dosage increased. The Marshall flow decreased, and the Marshall Quotient (MQ) increased with increasing the polyethylene dosage. The DSR results indicated that adding polyethylene resulted in extracted binders with improved elasticity (based on phase angle results). Finally, the authors suggested that the polyethylene dosage should be limited to 4% by weight of asphalt binder to yield modified asphalt mixtures with the optimum properties.

“Analysis of the Influence of using Recycled Polystyrene as a Substitute for Bitumen in the Behaviour of Asphalt Concrete Mixtures” by M. Vila-Cortavitarte, P. Lastra-Gonzalez, M.A. Calzada-Perez, and I. Indacoechea-Vega in *Journal of Cleaner Production*, 2017.

Authors	M. Vila-Cortavitarte, P. Lastra-Gonzalez, M.A. Calzada-Perez, and I. Indacoechea-Vega (University of Cantabria, Spain)
Sponsor	Unknown
Plastic Type	Polystyrene (PS)
Plastic Addition Method	Dry Process
Plastic Dosage	1 and 2% by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing, Environmental Impact Assessment

This research evaluated adding three types of polystyrene (PS) wastes as binder replacement in asphalt mixtures, which included the general-purpose polystyrene (GPPS), high impact polystyrene (HIPS), and polystyrene from hangers (HPS). Each waste polystyrene was added into the mixture via the dry process at two dosages: 1 and 2% by weight of asphalt binder. The dry process was selected over the wet process because of its technical simplicity. Various laboratory mixture performance tests including the indirect tensile strength (ITS) test, wheel tracking test, Particle loss (Cantabro) test, compatibility test, stiffness test (EN 12697-26), and fatigue resistance test (EN 12697-24) were conducted to evaluate the impact of PS wastes on the performance properties of asphalt mixtures. Moreover, life cycle assessment (LCA) was conducted to evaluate the environmental impacts of asphalt mixtures containing PS wastes. The mixture performance test results were compared among the three types of PS wastes at each dosage.

Test results showed that adding 1% PS as binder replacement significantly improved the performance properties, especially the rutting resistance, of the control asphalt mixture. However, adding 2% PS as binder replacement showed a lack of cohesion in the wheel tracking test. The LCA results predicted that using 1% PS could increase the lifespan of asphalt mixtures without increasing the environmental impacts from production and construction. The study also concluded that using the dry process of adding PS would not increase the production costs of asphalt mixtures since the process does not require significant plant modifications.

"Evaluating the Fatigue Properties of Hot Mix Asphalt Reinforced by Recycled PET Fibers using 4-point Bending Test" by Z. Dehghan and A. Modarres in *Journal of Construction and Building Materials*, 2017.

Authors	Z. Dehghan and A. Modarres (Babol Noshirvani University of Technology, Iran)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	0.5, 1.0, 1.5 and 2.0% by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the fatigue resistance of asphalt mixtures modified with polyethylene terephthalate (PET) fibers at different lengths (i.e., 1 cm and 2 cm) and crumb PET (Figure 27). PET fiber was added into the mixture via the dry process at dosages ranging from 0.5 to 2.0% by weight of asphalt binder. The crumb PET with particle size of 0.425 to 1.180 mm was added using the same process at 1.0 and 2.0% by weight of asphalt binder. The four-point bending test was conducted to evaluate the fatigue resistance of asphalt mixtures with and without PET modification.

Test results showed that the addition of PET fibers should be restricted to 2.0% to prevent the formation of fiber agglomeration zones. Overall, adding PET fibers and crumb PET reduced the flexural stiffness but improved the fatigue resistance of asphalt mixtures. At the same PET dosage, the 2 cm PET fiber yielded asphalt mixtures with better fatigue resistance than the 1 cm fiber. Finally, adding 1.0% PET fiber and 2.0% crumb PET were recommended as the optimum modification option for improving the fatigue resistance of asphalt mixtures.

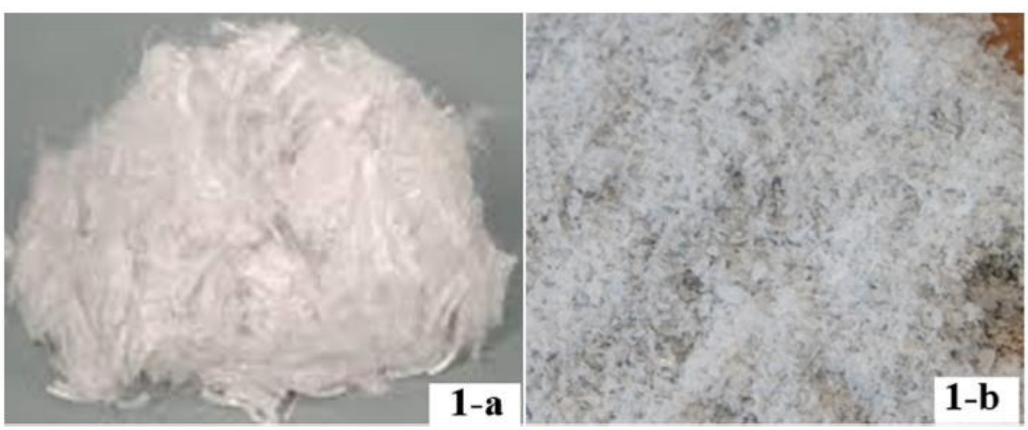


Figure 27. PET Fibers (left) and Crumb PET (Right) (Dehghan and Modarres, 2017)

“Effect of Cross-linkers on the Performance of Polyethylene-modified Asphalt Binders” by F.M. Nejad, R. Zarroodi, and K. Naderi in *Construction Materials*, 2017.

Authors	F.M. Nejad (Amirkabir University of Technology, Iran), R. Zarroodi (Islamic Azad University Tehran Science and Research Branch, Iran), and K. Naderi (Amirkabir University of Technology, Iran)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	3 and 7 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the effect of cross-linkers on the storage stability and fatigue performance of asphalt binders modified with high-density polyethylene (HDPE). The HDPE was obtained from a commercial source and had a melt flow index of 18, specific gravity of 0.952, and Vicat softening point of 122°C. The base binder used for HDPE modification had a 60/70 penetration grade. Two cross-linking agents were evaluated as potential compatibilizers for HDPE modified binders: polyphosphoric acid (PPA) and sulfur. For the preparation of HDPE modified binders, a high-shear mixer was used to blend the HDPE into asphalt binder for 45 minutes at 170°C. In cases where a cross-linking agent was used, PPA or sulfur was then added into the HDPE modified binder and blended for 30 minutes at 170°C. HDPE was added at two dosage rates: 3 and 7 percent by weight of asphalt binder. PPA was added at 1.5 percent by weight of asphalt binder, while sulfur was added at 0.5 percent by weight of HDPE. The modified binders were first tested using the cigar-tube separation test to determine their storage stability. Test results showed that HDPE modified binders without PPA or sulfur exhibited severe phase separation during high-temperature storage, which indicated a lack of compatibility between the HDPE and asphalt binder used. Adding sulfur did not improve the storage stability of HDPE modified binder; instead, HDPE plus sulfur modified binders showed more severe phase separation based on the softening point results. On the other hand, the addition of PPA was effective in mitigating the phase separation of HDPE modified binders. It was hypothesized that due to its acidic property, PPA transformed the sol state of asphalt binder into a gel-type structure, which contributed to enhanced cross-linking between the HDPE and asphalt binder and subsequently improved the storage stability of the modified binders. The linear amplitude sweep (LAS) test was conducted to determine the impact of HDPE modification on the fatigue characteristics of asphalt binders. In almost all cases, the modified binders outperformed the base binder in terms of fatigue life at strain levels lower than 1%, while the opposite trend was observed at higher strain levels. Adding PPA greatly improved the fatigue resistance of HDPE modified binders, while adding sulfur did not show any significant impact. Based on these results, PPA was recommended as a potential compatibilizer and performance-enhancing additive for HDPE modified binders.

"Effects of High-Density Polyethylene and Crumb Rubber Powder on Properties of Asphalt Mix" by N.M. Reddy and M.C. Venkatasubbaiah in *International Research Journal of Engineering and Technology*, 2017.

Authors	N.M. Reddy and M.C. Venkatasubbaiah (AITS, Rajampet, Andhrapradesh, India)
Sponsor	Unknown
Plastic Type	High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	3, 4, 5, and 6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study investigated the effects of HDPE and crumb rubber powder on the properties of asphalt mixtures. HDPE was provided in pellet form and had a specific gravity of 0.955 (Figure 28). The crumb rubber powder (CRP) had its particle size passing the ASTM #10 sieve. For binder evaluation, HDPE and crumb rubber powder were added using the wet process. The base binder used had a 60/70 penetration grade. Four dosages of HDPE (3, 4, 5, and 6 percent) and three dosages of CRP (5, 10, and 15 percent) were utilized by weight of asphalt binder. To prepare modified binders, HDPE was first added to asphalt binder at a shearing rate of 1,200 rpm for 15 minutes at 185°C. Then, CRP was added into the modified binder and high-speed sheared for 1.5 hours at 185°C followed by being stirred at a low rate of 200 rpm for 15 minutes. The dry process was used to prepare modified mixtures, where HDPE and CRP were added to hot aggregates and then mixed with asphalt binder. Both the unmodified control and modified mixtures were designed using the Marshall mix design procedure and had an optimum binder content of 6.3 percent. Test results indicated that the penetration decreased but the softening point increased with the increasing of both HDPE and CRP dosage, which indicated that the addition of HDPE and CRP resulted in an overall improvement in the binder's deformation resistance at moderate to high temperatures. However, the ductility decreased when HDPE and CRP were added to the asphalt binder. The Marshall test results showed that when 5 percent HDPE and 10 percent CRP were used as mixture modifiers, an increase in the Marshall stability was obtained. On the other hand, the flow value decreased with the addition of the modifiers, regardless of the HDPE and CRP dosages. Finally, the addition of HDPE and CRP also improved the rutting resistance of the asphalt mixture.

Figure 28. HDPE Pellet (Reddy and Venkatasubbaiah, 2017)

"Performance Evaluation of Hot Mix Asphalt Concrete by Using Polymeric Waste Polyethylene" by H. Jana, M.Y. Aman, M. Tawab, and K. Ali in *Modeling, Simulation and Optimization,* 2017.

Authors	H. Jana, M.Y. Aman (University Tun Hussein Onn Malaysia, Malaysia), M. Tawab, and K. Ali (Sarhad University of Science and Information Technology, Pakistan)
Sponsor	University Tun Hussein Onn Malaysia, Malaysia
Plastic Type	Recycled low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	Up to 16 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of polymeric waste polyethylene (PE) for asphalt modification via the wet process. The PE sample was obtained from white low-density polyethylene (LDPE) bags collected from local markets and domestic wastes, cleaned, and then shredded into particles with a size of 2 to 3 mm. The PE sample had a specific gravity of 0.94 and a melting temperature of 115°C. The base binder used for PE modification had an 80/100 penetration grade. The procedure used to prepare the polyethylene modified binders was not discussed. Modified binders containing up to 16 percent PE by weight of asphalt binder were tested for penetration, while those modified with up to 4 percent PE were tested for softening point and flash and fire points. Test results indicated that PE modification had a binder stiffening effect. All modified binders had reduced penetration values but increased softening points as compared to the base binder. The addition of up to 4 percent polyethylene also increased the fire and flash points of the base binder.

"Performance of Recycled Plastic Waste Modified Asphalt Binder in Saudi Arabia" by M.A. Dalhat and H.I. Al-Abdul Wahhab in *International Journal of Pavement Engineering*, 2017.

Authors	M.A. Dalhat and H.I. Al-Abdul Wahhab (King Fahd University of Petroleum and Minerals, Saudi Arabia)
Sponsor	King Fahd University of Petroleum and Minerals, Saudi Arabia
Plastic Type	Low-density Polyethylene (LDPE), High-density Polyethylene (HDPE), Polypropylene (PP)
Plastic Addition Method	Wet Process
Plastic Dosage	2, 4, 6, and 8 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Pavement Design

This study evaluated the use of recycled plastic waste for asphalt modification via the wet process. Three recycled plastic samples were tested, including a low-density polyethylene (LDPE), a high-density polyethylene (HDPE), and a polypropylene (PP). All plastic samples were collected from a local municipality recycling program and processed through washing, shredding, and grinding (Figure 29) for ease of blending with asphalt binder. Differential scanning calorimetry results showed that LDPE, HDPE, and PP had a melting point of 110, 132, and 162°C, respectively, and thus were considered suitable for asphalt modification. The base binder used for plastic modification had an upper PG temperature of 64°C. A high-shear mixer (5,000 rpm) was used to prepare the plastic modified binders; the mixing temperature and time required to achieve a homogeneous binder blend, however, varied among different plastics: 30 minutes at 160°C for LDPE, 60 minutes at 180°C for HDPE, and 50 minutes at 190°C for PP. Regardless of the plastic type, all modified binders had higher viscosity than the base binder. The increase in binder viscosity was more significant for HDPE and PP as compared to LDPE. The addition of LDPE, HDPE, and PP also had an impact on the binder's viscoelastic behavior. The plastic modified binders had higher complex shear modulus $|G^*|$, lower phase angle (δ), and higher $|G^*|/\sin(\delta)$ values than the base binder, which indicated better rutting resistance. However, because LDPE, HDPE, and PP are not elastomeric polymers, all plastic modified binders did not pass the agency's elastic recovery requirement. The asphalt stiffening effect due to plastic modification was also observed in the mixture resilient modulus (M_R) test, where the 2 percent PP modified mixture had the highest M_R stiffness, followed by 2 percent HDPE modified, 4 percent LDPE modified, and unmodified control mixtures, respectively. Finally, pavement design analyses using the MEPDG software were conducted to determine the impact of plastic modification on predicted pavement performance. An asphalt pavement consisting of a 20-cm asphalt surface layer and a 30-cm asphalt base layer was modelled using neat, LDPE modified, HDPE modified, and PP modified binders. All design parameters used in the modeling analyses were kept the same except the rheological properties of the asphalt binders. Analysis results indicated that plastic modification significantly improved the predicted rutting and top-down cracking performance of asphalt pavements. The improvement in rutting performance was more pronounced for PP than HDPE and LDPE.

Figure 29. Recycled Plastic Waste Samples before and after Processing (From Top to Bottom: LDPE, HDPE, and PP) (Dalhat and Wahhab, 2017)

“Plastic Waste as Strength Modifiers in Asphalt for A Sustainable Environment” by A.A. Badejo, A.A. Adekunle, O.O. Adekoya, J.M. Ndambuki, K.W. Kupolati, B.S. Bada, and D.O. Omole in *African Journal of Science, Technology, Innovation and Development*, 2017.

Authors	A.A. Badejo, A.A. Adekunle, O.O. Adekoya (Federal University of Agriculture, Nigeria), J.M. Ndambuki, K.W. Kupolati (Tshwane University of Technology, South Africa), B.S. Bada (Federal University of Agriculture, Nigeria), and D.O. Omole (Covenant University, Nigeria)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	1, 3, and 5 Percent by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the use of recycled polyethylene terephthalate (PET) as strength modifiers in asphalt mixtures. For the preparation of PET modified mixtures, shredded PET was added into the mixture via the dry process. The PET dosage ranged from 1 to 5 percent by weight of asphalt binder. At each PET dosage, two sets of modified mixtures were prepared: one using the “binder replacement” method and the other using the “direct addition” method. The Marshall stability test was conducted on the modified mixtures at various PET dosages and using different addition methods. In most cases, PET modified mixtures had lower Marshall stability and higher Marshall flow values than the unmodified mixture, indicating reduced mixture stability and resistance to deformation. The opposite trend, however, was observed for the 1 percent PET modified mixture prepared using the “direct addition” method. The Marshall test results of this modified mixture complied with the agency requirements. Therefore, 1 percent addition of recycled PET was recommended as a feasible approach of modifying asphalt mixtures.

“Rheological Properties Investigation of Bitumen Modified with Nanosilica and Polyethylene Polymer” by N. Bala, M. Napiah, I. Kamaruddin, and N. Danlami in *International Journal of Advanced and Applied Sciences*, 2017.

Authors	N. Bala, M. Napiah, I. Kamaruddin, and N. Danlami (Universiti Teknologi PETRONAS, Malaysia)
Sponsor	Universiti Teknologi PETRONAS, Malaysia
Plastic Type	Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of inorganic nanosilica for enhancing the rheological properties and oxidative aging resistance of asphalt binders modified with polyethylene polymer. The polyethylene sample was made of linear low-density polyethylene (LLDPE) and provided in pellet form. The base binder used for LLDPE and nanosilica modification had an 80/100 penetration grade. To prepare modified binders, a high-shear mixer (4,000 rpm) was employed to blend the LLDPE and nanosilica into asphalt binder for 2 hours at 150°C. The dosage of LLDPE was 6 percent by weight of asphalt binder, while nanosilica was added at 1 to 6 percent by weight of asphalt binder. The scanning electron microscopy images showed that the addition of nanosilica significantly improved the microstructure of LLDPE modified binder. This improvement was mainly due to the high surface area and energy of the nanosilica group, which reacted with the LLDPE and asphalt binder and prevented the coalescence of LLDPE particles. Adding nanosilica improved the temperature susceptibility and storage stability of LLDPE modified binder. Asphalt binders modified with nanosilica and LLDPE exhibited enhanced viscoelastic properties, specifically high-temperature rutting resistance, relative to the LLDPE modified binder. Finally, adding nanosilica improved the asphalt binder’s resistance to oxidative aging, where the LLDPE/ nanosilica modified binders had significantly less viscosity aging index and high temperature aging index than the control binder modified with LLDPE only. This improvement in oxidative aging resistance was attributed to the high surface area ratio of dispersed nanosilica layers in asphalt binder, which protected the penetration and diffusion of oxygen and loss of volatile components during aging.

"Storage Stability and High-temperature Performance of Asphalt Binder Modified with Recycled Plastic" by H.I. Al-Abdul Wahhab, M.A. Dalhat, and M.A. Habib in *Road Materials and Pavement Design*, 2017.

Authors	H.I. Al-Abdul Wahhab, M.A. Dalhat, and M.A. Habib (King Fahd University of Petroleum and Minerals, Saudi Arabia)
Sponsor	King Fahd University of Petroleum and Minerals, Saudi Arabia
Plastic Type	Recycled High-density Polyethylene (HDPE), Recycled Low-density Polyethylene (LDPE), Recycled Polypropylene (PP)
Plastic Addition Method	Wet Process
Plastic Dosage	2 to 8 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the storage stability and high-temperature performance properties of asphalt binders modified with recycled plastics. Recycled plastics were collected from the municipality collection point, sorted into similar categories, screened, and processed into powder or granulate form for asphalt modification. Dynamic scanning calorimetric analysis identified three types of recycled plastics as potential asphalt binder modifiers: low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP). The melting temperature of LDPE, HDPE, and PP was 110, 132, and 162°C, respectively. The base binder used had a performance grade (PG) of 64-22. In addition to plastics, styrene butadiene styrene (SBS) and plastomeric polybilt (PB) [ethylene-vinyl acetate (EVA) copolymer] were also used for asphalt modification. A high-shear mixer (5,000 rpm) was employed to prepare the modified binders. The mixing time and temperature varied among different types of plastics used; LDPE was mixed for 30 minutes at 160°C, HDPE for 60 minutes at 180°C, and PP for 50 minutes at 190°C. LDPE, HDPE, and PP were added at various dosages ranging from 2 to 8 percent by weight of asphalt binder. After modification, the binders were tested for viscosity, high-temperature PG, non-recoverable compliance, percent recovery, and storage stability. It was found that the viscosity and high-temperature PG of LDPE-SBS and PP-SBS modified binders increased as the LDPE, PP, or SBS percentage increased. The HDPE-SBS modified binders, however, showed a different trend; for those containing 4 percent HDPE or more, adding up to 1.5 percent SBS showed a reduction in the binder's viscosity and high-temperature PG, while the opposite trend was observed at higher SBS contents. Plastic modification improved the rutting resistance of the base binder but had no impact on its elasticity. The addition of SBS as an elastomer yielded modified binders with significantly better percent recovery results in the multiple stress creep recovery (MSCR) test. Finally, storage stability testing showed that PP modified binders were susceptible to phase separation, which was due to a lack of compatibility between the PP and asphalt binder used. Adding SBS or PB improved the storage stability of PP modified binders but was insufficient to mitigate the phase separation issue. The majority of LDPE or HDPE modified binders containing SBS or PB showed good storage stability under mild agitation.

“Use of Plastic Waste in Bituminous Pavement” by R.M. Anand and S. Sathya in *International Journal of ChemTech Research*, 2017.

Authors	R.M. Anand (Kumaraguru College of Technology, India) and S. Sathya (SNS College of Technology, India)
Sponsor	Unknown
Plastic Type	Not Specified
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: 10 Percent by Weight of Asphalt Binder Dry Process: Not Specified
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study presented limited laboratory test results on the impact of recycled plastics on the properties of aggregate and asphalt binder using the dry and wet process, respectively. The type of recycled plastics used, however, was not identified. When the dry process was used, plastics-coated aggregates showed better resistance to crushing, abrasion, and impact than the traditional uncoated aggregates. When the wet process was used, asphalt binders after plastic modification had lower penetration values and higher softening points, which indicated increased binder stiffness. Use of recycled plastics for asphalt modification also increased the Marshall stability of asphalt mixtures.

“Use of Waste Plastic Materials for Road Construction in Ghana” by J.K. Appiah, V.N. Berko-Boateng, and T.A. Tagbor in *Case Studies in Construction Materials*, 2017.

Authors	J.K. Appiah, V.N. Berko-Boateng (Kwame Nkrumah University of Science and Technology, Ghana), and T.A. Tagbor (Council for Scientific and Industrial Research-Building and Road Research Institute, Ghana)
Sponsor	Unknown
Plastic Type	Recycled High-density Polyethylene (HDPE), Recycled Polypropylene (PP)
Plastic Addition Method	Wet Process
Plastic Dosage	0.5 to 3 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the use of recycled high-density polyethylene (HDPE) and polypropylene (PP) for asphalt modification via the wet process. The base binder used had an AC-20 grade. For the preparation of HDPE or PP modified binder, a low-shear mixer (over 120 rpm) was used to blend the HDPE and PP into asphalt binder for at least 30 minutes at 160 to 170°C until a homogeneous binder blend was achieved. The dosage of HDPE and PP used ranged from 0.5 to 3 percent by weight of asphalt binder. Testing for penetration, softening point, and viscosity (at both 60°C and 135°C) tests was conducted to compare the physical properties of asphalt binders before and after HDPE or PP modification. Test results indicated that adding HDPE and PP reduced the penetration and increased the softening point and viscosity of the base binder, and that as the plastic dosage increased, the changes in these binder properties became more significant. Fourier transform infrared spectroscopy (FTIR) was also conducted to assess the dispersion of HDPE and PP in the modified binders. By comparing the intensity of three prominent peaks (3000-2850, 1465-1375, and 2400-2100 cm^{-1}) on the FTIR spectrum, 2 percent HDPE and 3 percent PP were identified as the optimum dosages for asphalt modification, which yielded the most compatible and homogenous modified binders.

"Utilization & Minimization of Waste Plastic in Construction of Pavement: A Review" by A. Chakraborty and S. Mehta in the *International Journal of Engineering Technology Science and Research*, 2017.

Authors	A. Chakraborty and S. Mehta (G D Goenka University, India)
Sponsor	Unknown
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Literature Review

This review article discusses the utilization and minimization of waste plastic for asphalt pavement construction. The article states that plastic modified binders are of better overall quality than unmodified binders. Specifically, the addition of recycled plastics increases the softening point but decreases the penetration of an asphalt binder. When added using the dry process, recycled plastics can reduce the porosity and moisture absorption of the aggregates due to surface coating. Asphalt mixtures containing plastic coated aggregates usually have higher Marshall stability values than those using uncoated aggregates, and thus, are expected to improve pavement performance and service life. In general, processing of recycled plastics consists of segregation, a cleaning process, a shredding process, and a collection process. Thermal characterization of polyethylene, polypropylene, and polystyrene shows that these polymers soften easily without any evolution of gas between 130 and 1400°C. The article identifies two potential environmental and safety concerns regarding the use of recycled plastic for asphalt pavement construction: leaching of toxic components during processing of recycled plastics, and the generation of chlorine-based gases during mixture production and construction. Finally, the article states that conventional asphalt pavements only last for 4 to 5 years while those using plastic modified asphalt mixtures can last up to 10 years.

"Bags, Bottles being Transformed into Roadways" by K. Tilley in *Plastics News* at https://www.plasticsnews.com/article/20180615/NEWS/180619927/bags-bottles-being-transformed-into-roadways, 2018.

Authors	K. Tilley
Sponsor	Not Applicable
Plastic Type	Waste Soft Plastics, Proprietary Product from Fulton Hogan
Plastic Addition Method	Not Specified
Plastic Dosage	Not Specified
Scope	Field Project

This newsletter article discusses three asphalt paving projects using recycled plastics modified asphalt mixtures. The first project was a 1,400-foot roadway section in a Melbourne suburb (Figure 30), which used approximately 200,000 soft plastics (including bags, toner from used printer cartridges, glass, and recycled asphalt). The project was a collaboration between Downer EDI Ltd. and two resource recovery and recycling companies in Australia. Downer claimed that the plastic modified binder was better than the straight-run virgin binder; therefore, its usage could yield asphalt mixtures with reduced susceptibility to cracking and fatigue damage for high traffic volume roadway applications. The second project was part of Christchurch International Airport's fire station in New Zealand. The project was constructed by Fulton Hogan using its proprietary PlastiPhalt® technology (https://www.fultonhogan.com/), which consumed 3,100 4-liter plastic oil containers. The third project was two 30-meter long bicycle paths in the Netherlands, which was commissioned by the Dutch community of Zwolle and constructed using hollow prefabricated plastic elements which enabled water drainage and laying down of cables and pipes.

Figure 30. Photo of an Asphalt Paving Project using Waste Plastic Modified Asphalt Mixtures in Melbourne, Australia (Tilley, 2018)

"Reuse of Agricultural Plastic Wastes for the Manufacturing of Roads Bituminous Mixtures, using the "Dry Way" Methodology" by M.J.S. López, P.P. López, M.E.H. Pérez, and J.T. Pérez in *Carreteras No. 217*, 2018.

Authors	M.J.S. López (Agencia de Obra Pública de la Junta de Andalucía, Spain), P.P. López (Universidad de Huelva, Spain), M.E.H. Pérez, and J.T. Pérez (EIFFAGE Infraestructuras, France)
Sponsor	Unknown
Plastic Type	Recycled Plastics from Agricultural Waste
Plastic Addition Method	Dry Process
Plastic Dosage	0.5% by Weight of Asphalt Mixture
Scope	Laboratory Mixture Testing, Field Project

In this study, the "dry process" was followed to incorporate recycled plastics while mixing the aggregate and binder to obtain asphalt mixtures with improved properties. The experimental plan included characterization and selection of the constituent materials (asphalt binder, agricultural waste plastics, etc.) as well as mixture characterization and performance testing. In addition, the plastic-binder interaction was studied with rheology and microstructural analysis. Two different recycled plastic products were obtained from agricultural waste from two provinces in Spain. Thermogravimetric analyses (TGA) were performed on these materials to identify their composition and degradation levels. This study utilized three binders with different penetration grades (B50/70, B160/220, B500). The dosage of recycled plastics added to the mix was 0.5% by weight of the mixture.

For mixture performance testing, the wheel tracking test was conducted for rutting evaluation, the bending beam test for fatigue evaluation, the tensile strength ratio (TSR) test for moisture damage evaluation, and the dynamic modulus test for stiffness characterization. Test results indicated that adding plastic waste increased the stiffness, improved the permanent deformation resistance, but reduced the fatigue resistance of the control mixture. A full-scale field experiment was conducted with a binder/plastic combination. Two 500-meter sections (experimental and control) were built on highway A-2005 in Cadiz, Spain, with a layer thickness of 4.5 cm. The experimental section was constructed with asphalt mixtures containing 0.3% recycled plastics. Field evaluation through one year of falling weight deflectometer (FWD) testing of these sections indicated that the experimental section had lower deflection than the control section. The study did not provide any further field performance comparisons.

"Value-added Application of Waste PET Based Additives in Bituminous Mixtures Containing High Percentage of Reclaimed Asphalt Pavement (RAP)" by Z. Leng, A. Sreeram, R.K. Padhan, and Z. Tan in *Journal of Cleaner Production*, 2018.

Authors	Z. Leng, A. Sreeram, R.K. Padhan, and Z. Tan (Hong Kong Polytechnic University, China)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Wet Process
Plastic Dosage	2% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the impacts of a polyethylene terephthalate (PET) based additive on the performance properties of asphalt binders containing reclaimed asphalt pavement (RAP). The PET additive was synthesized from PET particles through an aminolysis process, as shown in Figure 31. The additive was added into the virgin binder (with a penetration value of 69 at 25°C) at a dosage of 2.0% using a high-shear mixer (blending for two hours at 150°C at 4,000 RPM). Various laboratory binder tests were conducted to evaluate the stripping potential using the hot water and immersion tests; conventional physical properties using the penetration, softening point, and viscosity tests; rutting and cracking resistance using dynamic shear rheometer (DSR) and bending beam rheometer (BBR); and chemical properties using Fourier transform infra-red spectrometry (FTIR) and fluorescence microscopy (FM) of asphalt binders with and without RAP and the PET based additive. Test results indicated that adding the PET-based additive reduced the penetration and increased the softening point and viscosity of the asphalt binder. This trend was further enhanced by adding heavily aged RAP binder. The hot water and immersion test showed that adding PET reduced the stripping potential of asphalt binders containing RAP. The DSR and BBR results demonstrated that adding the PET-based additive improved the rutting resistance, fatigue resistance (based on $|G^*|\sin(\delta)$ parameter), and low-temperature cracking resistance of asphalt binders containing RAP. The FTIR spectroscopy analysis showed that asphalt binders modified with the PET-based additive were less susceptible to the formation of oxidative products upon aging. Finally, the FM analysis confirmed the homogeneity of the PET modified binders.

Figure 31. PET Derived Additive (Leng et al., 2018)

"Dow Joins Project Building Roads with Recycled LDPE" by J. Paben in *Plastics Recycling Update* at https://resource-recycling.com/plastics/2018/01/12/dow-joins-project-building-roads-recycled-ldpe/, 2018.

Authors	J. Paben
Sponsor	Not applicable
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Dry Process
Plastic Dosage	Not Specified
Scope	Field Project

This newsletter article discusses an asphalt paving project using asphalt mixtures modified with recycled low-density polyethylene (LDPE) in Indonesia. The project was constructed as a mile-long test road in Depok City, West Java. The plastic modified mixture was produced using the dry process. LDPE was first shredded into pieces of 9.5 mm or less and then washed and dried for contaminant removal. During mixture production, LDPE was added into hot aggregates for about 10 seconds, allowing it to melt and cover the surface of the aggregates. Then, LDPE-coated aggregates were mixed with asphalt binder for 35 seconds. Field performance of the project was monitored by the National Center for Road and Bridge Construction. Preliminary performance data indicated that the plastic modified mixture using LDPE-coated aggregates was more resistant to deformation and fatigue cracking than the conventional unmodified mixture.

"Enhancement of Storage Stability and Rheological Properties of Polyethylene (PE) Modified Asphalt using Cross Linking and Reactive Polymer Based Additives" by R.K. Padhan and A. Screeram in *Construction and Building Materials*, 2018.

Authors	R.K. Padhan (Indian Oil R&D Centre, India) and A. Screeram (Hong Kong Polytechnic University, China)
Sponsor	Unknown
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study explored the use of cross-linking and reactive polymer-based additives to improve the storage stability and rheological properties of asphalt binders modified with recycled low-density polyethylene (LDPE). The base binder used had an AC-10 grade. As shown in Figure 32, the recycled LPDE was obtained from waste plastic bags and cut into approximately 5 cm by 5 cm pieces for ease of mixing with asphalt binder. Trans-polyoctenamer (TPOR), with a molecular weight of 90,000, was the reactive polymer-based additive used with LDPE for asphalt modification. Sulfur was added as a cross-linking additive for LDPE plus TPOR modified binders. For the preparation of LDPE modified binders, a high-shear mixer (4,000 rpm) was first used to blend the LDPE and TPOR into asphalt binder for 1 hour at 165°C. Then, sulfur was added and high-shear blended into the modified binder for 30 minutes at 165°C. LDPE and TPOR were added at 2 and 1 percent by weight of asphalt binder, respectively, while sulfur was added at three dosages: 0.1, 0.5, and 1.0 percent by weight of asphalt binder. Laboratory binder tests were conducted to determine the storage stability and rheological properties of LDPE plus TPOR modified binders. Test results indicated that adding sulfur as a cross-linking additive improved the storage stability, morphology, and elasticity of modified binder containing LDPE and TPOR. This improvement was attributed to the vulcanization of TPOR due to the addition of sulfur, which contributed to formation of highly interlinked polymer network ensuring a stable vulcanized TPOR matrix (Figure 33). LDPE plus TPOR modified binders with and without sulfur showed consistently higher viscosity and softening point but lower penetration values than the base binder, which indicated the stiffening effect due to use of LDPE and TPOR for asphalt modification. Finally, adding LDPE, TPOR, and sulfur in combination improved the rutting and low-temperature cracking resistance of the base binder but had no impact on its fatigue resistance.

Figure 32. Waste Plastic Bags and Cut LDPE Pieces for Asphalt Modification (Padhan and Screeram, 2018)

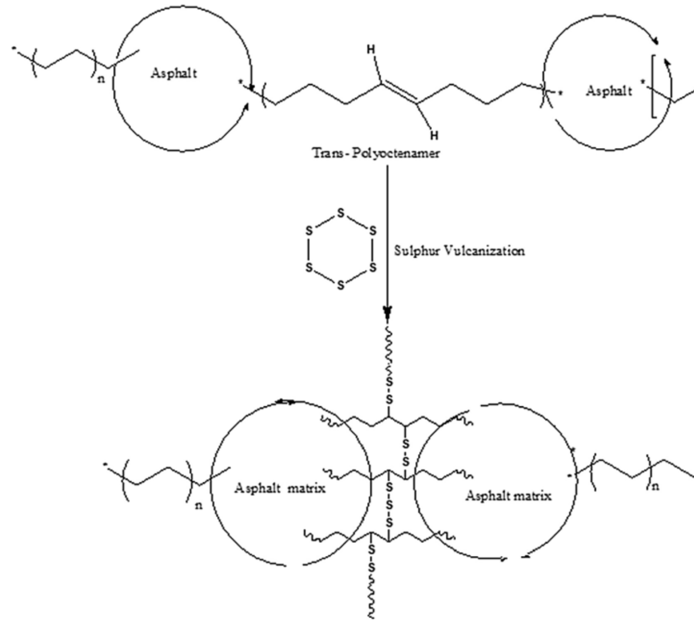


Figure 33. Reaction Mechanism of Vulcanization of Trans-polyoctenamer (Padhan and Screeram, 2018)

"Investigations of Rheological Properties of Asphalt Binders Modified with Scrap Polyethylenes" by S. Amirkhanian in *A Report Submitted to Plastics Industry Association*, 2018

Authors	S. Amirkhanian (Asphalt Technologies LLC)
Sponsor	Plastics Industry Association
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	2, 4, and 6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the rheological properties of asphalt binders modified with scrap polyethylene (PE). Three PE samples were tested, with each added at 2, 4, and 6 percent by weight of asphalt binder. Two PG 64-22 base binders were used for PE modification. For the preparation of PE modified binders, a low-shear mixer (700 rpm) was used to blend PE into asphalt binder for 2 hours at 177°C. Two styrene-butadiene-styrene (SBS) modified binders (PG 76-22) and two crumb rubber modified (CRM) binders were included for performance comparison purposes. Brookfield rotational viscosity test, performance grading, multiple stress creep recovery test (MSCR), linear amplitude sweep (LAS) test, and frequency sweep and amplitude sweep test were conducted to compare the rheological properties of the base, PE modified, SBS modified, and CRM modified binders. Test results indicated that adding PE increased the rotational viscosity and high-temperature PG of the base binder, which was likely to provide enhanced rutting resistance. However, this improvement might also have a side effect on the workability and compactability of the resultant asphalt mixtures. PE modified binders outperformed the unmodified control binders in the MSCR test in terms of higher percent recovery (%R) and lower non-recoverable compliance (J_{nr}) values, indicating better elasticity and rutting resistance. PE modification had a negative effect on the low-temperature properties of asphalt binders. In almost all cases, PE modified binders had higher (less negative) low-temperature PGs than the unmodified control binders. No consistent trend was observed regarding the impact of PE modification on the fatigue resistance of asphalt binders; PE modified binders generally outperformed the unmodified control binders in the LAS test, but not according to the Superpave G*sin(δ) parameter results. Finally, the impact of PE modification on the rheological properties of asphalt binders was found to be dependent upon binder source.

“Preparation Methods and Performance of Modified Asphalt Using Rubber-Plastic Alloy and Its Compounds” by F. Zhang, J. Li, M. Yaseen, M. Han, Y. Yin, and S. Yang in *Journal of Materials in Civil Engineering*, 2018.

Authors	F. Zhang, J. Li, M. Yaseen, M. Han, Y. Yin, and S. Yang (Guangxi University, China)
Sponsor	National Natural Science Foundation of China, Youth Project in the Guangxi Department of Education, China
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	0.75 to 10.5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

In this study, asphalt binders modified with different raw materials, including waste tire-rubber powder, recycled LDPE, styrene-butadiene-styrene (SBS), epoxy fatty acid methyl ester (EFAME), naphthenic oil, fluorocarbon surfactant, and sulfur, were prepared by two different approaches: melting-blending thermal plastic elastomers (TPE) with the raw materials, and direct mixing the asphalt binder with the raw materials in a single step. The base binder used had a 70-penetration grade. The rubber-plastic compound-modified binders were prepared in two steps. In the first step, the asphalt binder was heated for 3 hours at 135°C and then raised to a temperature of 170°C. The asphalt binder was then poured into a high-shear mixing emulsifier, where a fixed amount of composite mixture containing waste rubber powder, waste polyethylene particles, SBS, and additives was added. The shearing was performed at 180 to 185°C at a rotating speed of 6,900 rpm for 30 minutes. In the second step, the modified binder that had experienced the high-speed shearing in the first step was transferred into a high-speed disperser and was allowed to swell at 180°C at 500 rpm for 1 hour, followed by the addition of a stabilizer, after which it was allowed to swell for 3 hours until the end of the reaction. For asphalt modification, the rubber-plastic compound was added at four different dosages of 5, 15, 20, and 30 percent by weight of asphalt binder, while the proportion of recycled LDPE in the rubber-plastic compound varied from 15 to 35 percent by weight. The resultant dosage of recycled LDPE in the modified binders varied from 0.75 to 10.5 percent by weight of asphalt binder. Test results showed that the modified binders exhibited higher values of softening point and ductility in comparison to the unmodified base binder. The addition of the high-plastic compound (containing 35 percent recycled LDPE) resulted in a much harder mass and a net-like structure of asphalt binder, and hence, led to a decrease in penetration and ductility of the resultant modified binder. Concomitantly, the obtained high softening temperature demonstrated a harder mass of this modified binder, exhibiting stronger bonds compared to the other binders tested. On the other hand, a high degree of segregation (i.e., poor compatibility), interaction, and bonding was observed for the high-plastic compound. Based on these results, it was concluded that the compound-modified approach ranked higher in terms of the macro performance than the TPE method for the preparation of modified binders; therefore, the former was recommended as a choice for industrial-level applications.

“Recycled Plastic used in Airport Asphalt” in Roads & Infrastructure Magazine at http://www.roadsonline.com.au/recycled-plastic-used-in-airport-asphalt/, 2018.

“Trial Recycles Plastic Containers into Asphalt” by Fulton Hogan at https://www.fultonhogan.com/trial-recycles-plastic-containers-asphalt/, 2018.

Authors	Fulton Hogan, Roads & Infrastructure Magazine (New Zealand)
Sponsor	Not Applicable
Plastic Type	Waste Plastic Containers, Proprietary Product from Fulton Hogan
Plastic Addition Method	Not Specified
Plastic Dosage	Not Specified
Scope	Field Project

These newsletter articles discuss the successful completion of an asphalt paving project using asphalt mixtures modified with recycled waste plastic in New Zealand. The project was a collaboration between Fulton Hogan and Christchurch International Airport. Half of the airport’s fire station was paved with PlastiPhalt®, a proprietary asphaltic product developed and manufactured by Fulton Hogan (https://www.fultonhogan.com/). This product is produced by shredding used plastic containers and then granulating them to an ideal size for asphalt modification. The specific type and dosage of plastic used was not provided. Approximately 250 tons of PlastiPhalt® mixtures were laid in the project, which consumed 3,100 four-liter plastic oil containers.

"Recycled Waste Plastic for Extending and Modifying Asphalt Binders" by G. White and G. Reid at the *8th Symposium on Pavement Surface Characteristics: SUFF 2018 – Vehicle to Road Connectivity*, 2018.

Authors	G. White (University of the Sunshine Coast, Australia) and G. Reid (MacRebur, United Kingdom)
Sponsor	Unknown
Plastic Type	Proprietary Products from MacRebur
Plastic Addition Method	Dry Process
Plastic Dosage	6 Percent by Volume of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory MixtureTesting, Cost Analysis

This study explored the use of three proprietary recycled plastic products for asphalt modification. The plastic products, provided by MacRebur (https://www.macrebur.com/), claimed to be produced from 100 percent recycled waste. As shown in Figure 34, one product (MR8) was in shredded form and the other two (MR6 and MR10) were in pellet form. The plastic products were introduced into asphalt mixtures using the dry process. The dosage used was to replace 6 percent by volume of asphalt binder. Two asphalt mixtures with a 40/60 penetration grade binder were included for laboratory testing: a dense-graded base course (AC20) mixture and a gap-graded surface course (SMA10) mixture. Each mixture, before and after plastic modification, was evaluated under the British specifications for road asphalt mixtures. Laboratory test results showed that the AC20 mixture modified with MR6 exhibited higher stiffness and better resistance to rutting and moisture damage compared to the unmodified control mixture. Furthermore, using MR6, MR8, and MR10 for asphalt modification increased the stiffness, rutting resistance, and fracture toughness of the SMA10 mixture; however, the impact on resistance to moisture damage was mixed among the three products. Finally, a simplified cost-benefit analysis was conducted, concluding that the use of MR6 and MR10 at 6 percent volume replacement can be a cost-effective alternative to typical modified binders used in Australia.

Figure 34. MacRebur's Recycled Plastic Products; From Left to Right: MR6, MR8, and MR10 (White and Reid, 2018)

“Benefits of Utilization the Recycle Polyethylene Terephthalate Waste Plastic Materials as a Modifier to Asphalt Mixtures” by I.A. El-Naga and M. Ragab in *Construction and Building Materials*, 2019.

Authors	I.A. El-Naga (Tanta University, Egypt) and M. Ragab (Suez University, Egypt)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene Terephthalate (PET)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: 2 to 12 Percent by Weight of Asphalt Binder Dry Process: 10 to 15 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing, Pavement Design

This study investigated the effect of using PET waste plastic materials for improving the performance of asphalt binders and mixtures. Firstly, PET was evaluated as a modifier of asphalt binder at dosages ranging among 2, 4, 6, 8, 10, and 12 percent by weight of asphalt binder. Secondly, PET was evaluated as a modifier to the asphalt mixture at dosages ranging among 10, 11, 12, 13, 14, and 15 percent by weight of asphalt binder. The base binder used had a 60/70 penetration grade. PET was obtained and processed from waste plastic bottles and had a specific gravity of 0.9 and a melting point of 182°C. A 44.4 percent reduction in penetration was observed when adding 12 percent PET into the asphalt binder. On the other hand, a 13.4 percent increase in the softening point, 11.2 percent increase in the flash point, and 22.1 percent increase in the absolute viscosity were found when the asphalt binder was modified with 12 percent PET. Mixture test results indicated that PET modified mixtures had higher Marshall stiffness modulus, indirect tensile strength, and rutting resistance than the unmodified control mixture. The air voids and voids in mineral aggregate of compacted specimens increased as the PET dosage increased. Adding PET also showed a positive impact on improving the rutting resistance of asphalt mixtures in the wheel tracking test. Finally, pavement design analysis conducted using the KENPAVE software showed that the pavement life could be increased by 2.81 times when the surface layer was modified with 12 percent PET as a mixture modifier.

“Burnside Parking Lot Partially Paved with Plastic” by CBC News at https://www.cbc.ca/news/canada/nova-scotia/plastic-paving-demonstration-burnside-1.5216895, 2019.

Authors	CBC News (Canada)
Sponsor	Goodwood Plastic Products (Canada)
Plastic Type	Plastic Shopping Bags
Plastic Addition Method	Not Specified
Plastic Dosage	Not Specified
Scope	Field Project

This newsletter article discusses the successful completion of a demonstration paving project using asphalt mixtures modified with recycled plastics. The project was a parking lot in Burnside, Nova Scotia. It consumed two tons of material made from plastic shopping bags. Information about the dosage of plastics used and how they were added into the mixture was not discussed. The article claimed that the plastics replaced 25 percent of asphalt binder used in the mixture and that the resultant modified mixture could be less susceptible to free-thaw cycle due to increased flexibility. Figure 35 presents two photos from the construction of the project.

Figure 35. Construction of a Parking Lot using Asphalt Mixtures Modified with Plastic Shopping Bags (CBS News, 2019)

"Dow Completes Roads Improved with Recycled Plastic" by Dow Corporate at https://www.dow.com/en-us/news/dow-completes-roads-improved-with-recycled-plastic.html, 2019.

"Dow Mixes Post-Consumer Plastic into Asphalt Roads" by Construction Equipment Guide at https://www.constructionequipmentguide.com/dow-mixes-post-consumer-plastic-into-asphalt-roads/44446, 2019.

Authors	Dow Corporate, Construction Equipment Guide
Sponsor	Not Applicable
Plastic Type	Recycled Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	1.5 Percent by Weight of Asphalt Binder
Scope	Field Project

These newsletter articles discuss the successful completion of two demonstration paving projects using asphalt mixtures modified with recycled plastics. These projects corresponded to two private roads at Dow's Freeport, Texas, facility. The binder formulation incorporated the use of recycled linear low-density polyethylene (LLDPE) and Dow ELVALOY™ RET asphalt modification technology. The dosages of LLDPE and ELVALOY™ used, however, were not discussed. The final modified binder met Texas Department of Transportation's PG 70-22 requirements. According to Dow, these two demonstration projects used 1,686 pounds of recycled LLDPE and covered approximately 2,600 feet of asphalt roads. Dow researchers plan to monitor the longevity and performance of these demonstration projects to further improve the binder formulations for a variety of climates and conditions. One of the articles also references several demonstration paving projects constructed in Indonesia, India, and Thailand over the last two years.

“Dow Incorporates Recycled Plastic into Michigan Roads and Parking Lots” by Dow Corporate at https://www.dow.com/en-us/news/dow-incorporates-recycled-plastic-into-michigan-roads-and-parkin.html, 2019.

“Recycled Plastic in Modified Asphalt” in *Association of Modified Asphalt Producers (AMAP) December 2019 Newsletter*, 2019.

Authors	Dow Corporate, Association of Modified Asphalt Producers
Sponsor	Not Applicable
Plastic Type	Plastic Scrap from Winpak
Plastic Addition Method	Wet Process
Plastic Dosage	1.2 Percent by Weight of Asphalt Binder
Scope	Field Project

These newsletter articles discuss the successful completion of six demonstration paving projects in Michigan using asphalt mixtures modified with recycled plastics. These projects included four county roads in Larkin Township and Bullock Creek, as well as two parking lots at the Global Dow Center in Midland and Saginaw Valley State University. The binder formulation was enabled by Dow ELVALOY^{TM} asphalt modification technology and targeted a PG 64-28P binder grade per the Michigan DOT specification. The post-industrial scrap was a mixed polyethylene-rich packaging stream containing approximately 25 percent engineering resins with a melting point above 185°C. According to Dow, the goal of these demonstration projects was to “help develop new end-use markets that maintain the value of recycled plastics.” The projects used more than 10,400 lbs. of recycled plastics and covered 5.5 lane miles of asphalt roads and 30,500 square yards of parking surface. Dow researchers indicated that the preliminary performance results were promising and that they will continue to monitor the longevity and field performance of these projects over time.

"Evaluating Recycled Waste Plastic Modification and Extension of Bituminous Binder for Asphalt" by G. White at the *18th Annual International Conference on Pavement Engineering*, 2019.

Authors	G. White (University of Sunshine Coast, Australia)
Sponsor	Unknown
Plastic Type	Proprietary Products from MacRebur
Plastic Addition Method	Wet Process
Plastic Dosage	6 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study evaluated the use of three proprietary recycled plastic products for asphalt modification via the wet process. The plastic products, referred to as MR6, MR8, and MR10, were provided by MacRebur (https://www.macrebur.com/). The base binder used for plastic modification had a 40/60 penetration grade. Each plastic product was added at 6 percent by weight of asphalt binder; however, the procedure used to prepare modified binders was not discussed. Leachability of chemicals and hazardous fume generation were evaluated for the asphalt binder before and after plastic modification. For the leachability evaluation, the asphalt binder was first placed in deionized water for 18 hours at 40°C. The water was then cold evaporated, and the residual was dissolved in ethanol and analyzed for mass spectrometry by gas chromatography. For the fume generation evaluation, the asphalt binder was thermally desorbed at temperatures ranging from 100 to 200°C and then analyzed for mass spectrometry by gas chromatography. The spectrometry analysis results showed that the three plastic products had no adverse impact on either the leachability or fume generation. Both unmodified and modified binders were also used to prepare 10 mm maximum sized stone mastic asphalt (SMA) surface mixtures for performance testing. Each mixture was tested using the indirect tensile stiffness modulus test, tensile strength ratio, wheel-tracking rutting test, semi-circular fracture toughness test, and indirect tensile fatigue test. Test results indicated that adding the three plastic products significantly increased the stiffness and rutting resistance of the SMA mixture but had no significant impact on its resistance to moisture damage. When tested under a stress-control condition, plastic modified mixtures showed higher fracture toughness than the control mixture. When tested under a strain-control condition, the use of MR6 and MR10 for asphalt modification increased the fatigue life of the SMA mixture, while adding MR8 had no improvement over the control mixture.

“Los Angeles is Testing ‘Plastic Asphalt’ that Makes it Possible to Recycle Roads” by A. Peters in *Fast Company – World Changing Ideas* at https://www.fastcompany.com/90450827/its-official-data-visualization-has-gone-mainstream, 2019.

Authors	A. Peters
Sponsor	Not Applicable
Plastic Type	Recycled Polyethylene Terephthalate (PET) from TechniSoil Industrial
Plastic Addition Method	Plastic Synthetic Binder
Plastic Dosage	Not Applicable
Scope	Field Project

This newsletter article discusses the plan of the City of Los Angeles to repave a street in the downtown area using materials made in part from waste plastic bottles in December 2019. This will be the first time for the city to mill off an existing asphalt pavement and fully recycle it in place using a synthetic binder rather than asphalt binder. The synthetic binder, developed by TechniSoil Industrial (https://technisoilind.com/), is made of recycled polyethylene terephthalate (PET). The company claimed that based on laboratory test results, using PET synthetic binder can make pavements last eight to 13 times longer than using a conventional asphalt binder. Construction of the project in the City of Los Angeles will require a continuous “recycling train,” as shown in Figure 36, for in-place recycling. Upon its successful completion, a follow-up two-year demonstration project on heavy-volume roadways through the area will then be constructed.

Figure 36. Photo of a Continuous “Recycling Train” for In-Place Recycling using PET Synthetic Binder (Peters, 2019).

“Novophalt Field Project List” by W. Tappeiner in *Email Communications*, 2019.

Authors	W. Tappeiner
Sponsor	Not Applicable
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Wet Process (Novophalt®)
Plastic Dosage	Not Applicable
Scope	Field Project

The Novophalt® technology was developed in Australia in the early 1980s and was commercially used since the mid-1980s in over a dozen countries. It first used virgin low-density polyethylene for asphalt modification and later focused on the use of selected recycled low-density polyethylene, linear low-density polyethylene, and ethene-vinyl-acetate. A list of field projects constructed using Novophalt® from 1982 to 2002 was provided. These projects were located in 19 countries, including Austria (14), Canada (2), China (20), Czech Republic (9), Egypt (5), Greece (2), Hungary (11), Ireland (1), Italy (13), Kuwait (1), Malaysia (1), Saudi Arabia (5), Spain (19), United Arab Emirates (1), United Kingdom (4), and United States (36). The Novophalt® projects included city streets, county roads, minor and principal arterials, interstates, and airports. However, field performance data is not available. A full list of these projects can be provided upon request.

“On the Road to Solving our Plastic Problem” in University of California, San Diego News Center at https://ucsdnews.ucsd.edu/feature/on-the-road-to-solving-our-plastic-problem, 2019.

“The First Road Made From Plastic Waste Was Just Finished in the US” by J. McCarthy in *Global Citizen* at https://www.globalcitizen.org/en/content/plastic-road-california-environment/, 2019.

Authors	University of California, San Diego, J. McCarthy
Sponsor	Not Applicable
Plastic Type	Proprietary Product from MacRebur
Plastic Addition Method	Not Specified
Plastic Dosage	Not Specified
Scope	Field Project

This newsletter article discusses the successful completion of an asphalt paving project using asphalt mixtures modified with recycled plastics on the campus of University of California, San Diego. The project was constructed using MacRebur’s “plastic road” technology (https://www.macrebur.com/). Detailed information regarding the type and dosage of recycled plastics used was not provided. Figure 37 presents photos taken during the construction of the project. The university will monitor the pavement performance over time and determine its viability for usage beyond the San Diego area.

Figure 37. Photos of an Asphalt Paving Project using MacRebur’s “Plastic Road” Technology on the Campus of University of California, San Diego (University of California, San Diego News Center, 2019)

“Parking Lot at New Sobeys in Timberlea Largely Made from Recycled Plastics” by CBC News at https://www.msn.com/en-ca/news/canada/parking-lot-at-new-sobeys-in-timberlea-largely-made-from-recycled-plastics/ar-BBXFh9g, 2019.

Authors	CBC News (Canada)
Sponsor	Sobeys (Canada)
Plastic Type	Plastic Shopping Bags
Plastic Addition Method	Not Specified
Plastic Dosage	Not Specified
Scope	Field Project

This newsletter article discusses the successful completion of a demonstration paving project using asphalt mixtures modified with recycled plastics. The project was a parking lot in Timberlea, Nova Scotia. It was a collaboration between Sobeys and Goodwood Plastic Products. The amount of recycled plastics used in the project equaled to more than six million plastic shopping bags. No further information about the project was provided.

“Performance Evaluation and Chemical Characterization of Asphalt Binders and Mixtures Containing Recycled Polythylene” in F. Yin, R. Moraes, M. Fortunatus, N. Tran, M.D. Elwardany, and J. Planche in *A Report Submitted to Plastics Industry Association*, 2019.

Authors	F. Yin, R. Moraes, M. Fortunatus, N. Tran (National Center for Asphalt Technology), M.D. Elwardany, and J. Planche (Western Research Institute)
Sponsor	Plastics Industry Association
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	2 to 5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This report summarizes a research study on the performance evaluation and chemical characterization of asphalt binders and mixtures containing recycled polyethylene. The wet process was used to add rPE for asphalt modification. The rPE sample was provided in pellet form and had a specific gravity of 0.939, an ash content of 7.1%, a melting temperature of 120°C, and a polymer resin makeup of 94% low-density polyethylene and 6% high-density polyethylene combined. A PG 58-28 asphalt binder was used for rPE modification. Two ethylene-based elastomeric reactive terpolymers (RET) were evaluated as potential compatibilizers to mitigate the phase separation of rPE modified binders. The elastomeric nature of the RET additives was also expected to yield resultant modified binders with enhanced fatigue tolerance and overall flexibility, providing performance benefits. The procedure used to prepare rPE modified binders is briefly summarized as follows: first, the PG 58-28 base binder was preheated for 2 hours at 180°C., then the rPE sample was added to the binder and blended for 1 hour using a high-shear mixer (3,000 rpm). In cases where a RET additive was used, the rPE modified binder was then transferred to a low-shear mixer (200 rpm) and blended for 10 minutes at 180°C. Finally, the RET additive and a crosslinking agent [polyphosphoric acid (PPA)] were added to the modified binder and blended for 1 to 2 hours until a homogeneous binder blend was achieved. Figure 38 illustrates the blending procedure.

Figure 38. Preparation of rPE and rPE plus RET Modified Binders (Yin et al., 2019)

A total of nine rPE modified binders were prepared; four of them were modified with 2 to 5 percent rPE (by weight of asphalt binder), while the other five were modified with a combination of rPE and RET. All modified binders were first tested for storage stability (based on softening point) and only those passing the specified requirement were further evaluated in three complementary experiments. The first experiment focused on binder rheological evaluation, where performance grading, delta Tc, multiple stress creep compliance (MSCR), linear amplitude sweep, and Glover-Rowe parameter tests were conducted. The second experiment focused on binder chemical evaluation, where four selected binders were characterized using Fourier-transform infrared spectroscopy, differential scanning calorimetry, saturate, aromatic, resin, and asphaltenes determinator, and gel permeation chromatography. The last experiment focused on mixture performance testing, where binder bond strength, Hamburg wheel tracking test, indirect tensile cracking test, disc-shaped compact tension test, and Texas overlay test were conducted to determine the impact of rPE and rPE plus RET on the performance properties of asphalt mixtures.

It was found that some of the modified binders passing the storage stability requirement (based on softening point) still showed phase separation when cooled to ambient temperature without shear agitation. This observation was confirmed in a modified storage stability test based on the MSCR testing of the top versus bottom cigar-tube binder samples. Adding 2 and 3 percent rPE increased the stiffness and rutting resistance of the base binder but had no effect on its low-temperature cracking, fatigue cracking, and block cracking resistance. Using rPE plus RET for asphalt modification significantly increased binder elasticity, rutting resistance, and fatigue resistance, but had no impact on low-temperature cracking resistance. Both modified binders containing rPE and rPE plus RET showed enhanced aging resistance over the base binder. rPE modified binders showed warmer (less negative) glass transition temperatures with relatively larger glass transition width, which was indicative of a more complex system relative to the base binder. The 3 percent rPE modified mixture had improved rutting resistance but reduced moisture resistance as compared to the unmodified control mixture. Adding 3 percent rPE plus 1.2 percent RET significantly improved the rutting and moisture resistance of the control mixture. The improvement in moisture resistance, however, was likely attributed to the inclusion of PPA as a crosslink agent for the RET additive used. Finally, using rPE or rPE plus RET for asphalt modification did not show a significant impact on the mixture resistance to intermediate-temperature fatigue cracking, thermal cracking, or reflective cracking.

“Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification” by M.A. Dalhat, H.I. Wahha, and K. Al-Adham in *Journal of Materials in Civil Engineering*, 2019.

Authors	M.A. Dalhat (Imam Abdulrahman Bin Faisal University, Saudi Arabia), H.I. Wahha, and K. Al-Adham (King Fahd University of Petroleum and Minerals, Saudi Arabia)
Sponsor	King Fahd University of Petroleum and Minerals, Saudi Arabia, Imam Abdulrahman Bin Faisal University, Saudi Arabia
Plastic Type	Blend of Recycled Low-density Polyethylene (LDPE), Recycled High-density Polyethylene (HDPE), Recycled Polypropylene (PP), Recycled Polyvinyl Chloride (PVC), and Recycled Polystyrene (PS)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Not Specified
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

In this study, a combined form of recycled plastic waste (RPW) was used as a mineral aggregate supplement in a dense-graded asphalt mixture containing an asphalt binder modified with RWP. The asphalt binder used had a performance grade (PG) of 64S-22, and its chemical composition was 19.2 percent asphaltenes, 24.7 percent aromatics, 27.2 percent saturates, and 28.8 percent resins. The asphalt binder was modified with RPW along with a plastomeric by-product polymer (PB) and styrene-butadiene-styrene (SBS) to yield a PG of 76H-10. RPW was obtained from municipality collection points and shredded for better handling as aggregates (Figure 39). The polymer resin makeup of RPW consisted approximately of 17 percent LDPE, 25 percent HDPE, 34 percent PET, 11 percent PP, 4 percent PVC, and 9 percent polystyrene (PS). Dynamic modulus, flow number, asphalt pavement analyzer, and flexural fatigue beam tests were employed to evaluate the performance of the hybrid RPW modified asphalt mixtures as compared to unmodified and crumb-rubber (CR) modified mixtures. Based on the evaluation of moisture sensitivity using indirect tensile strength and resilient modulus tests, RPW with more fine sizes (No. 8 to No. 40) were found more suitable than RPW with more coarse sizes (No. 8 to No. 10) for aggregate substitution in dense-graded mixtures. The dynamic modulus and flow number test results identified the optimum content of RPW aggregate as 9.5 percent. Asphalt mixtures containing a combined form of RPW aggregate showed better overall viscoelastic properties than those containing only PET aggregate. Furthermore, the hybrid RPW mixtures had higher stiffness and better rutting resistance than CR modified mixtures. Finally, adding RPW also improved the fatigue life of asphalt mixtures when utilized as a mineral aggregate supplement. Future research was recommended to investigate the RPW-mineral aggregate interaction and the effect of RPW aggregate phase change cycle on the volumetric and performance properties and asphalt mixtures.

Figure 39. Combined RPW Aggregate Substitute (Dalhat et al., 2019)

"Storage Stability Testing of Asphalt Binders Containing Recycled Polyethylene Materials" by F. Yin and R. Moraes in *A Research Report Submitted to Plastics Industry Association*, 2018.

"Storage Stability Testing of Asphalt Binders Containing Recycled Polyethylene Materials (Phase II-B Study)" by F. Yin, P. Turner, and R. Moraes in *A Research Report Submitted to Plastics Industry Association*, 2019.

Authors	F. Yin, R. Moraes, and P. Turner (National Center for Asphalt Technology)
Sponsor	Plastics Industry Association
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	2 to 5 Percent by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

These two reports summarize the results and findings of the storage stability testing of asphalt binders containing recycled plastics [mainly recycled polyethylene (rPE)]. Four rPE samples were tested and provided in pellet form (Figure 40). Two PG 58-28 asphalt binders from different crude sources were used for rPE modification. Each rPE was added at a dosage of 5 percent by weight of asphalt binder. Two compatibilizers were evaluated to determine their effects on mitigating the phase separation between rPE and asphalt binder. To prepare rPE modified binders, a high-shear mixer (3,000 rpm) was used to blend the rPE and compatibilizer (if used) into asphalt binder for 1 hour at 180°C. It was observed that after blending, all rPE samples were well dispersed in the asphalt binder with no coalescence of undissolved rPE particles observed. A total of 12 modified binders were prepared, including eight without compatibilizers and four with compatibilizers. Each modified binder was tested for storage stability (ASTM D7173) followed by softening point (ASTM D36). The pass/fail criterion used was a maximum allowable difference of 10°C in the softening point between the top and bottom cigar-tube binder samples per Georgia Department of Transportation specifications. Test results showed that none of the 5 percent rPE modified binders passed the specified storage stability requirement. Phase separation was observed in all binder samples. In all cases, the top cigar-tube binder sample had a softening point above 80°C, while the bottom sample had a softening point ranging from 43 to 50°C. Phase separation was also confirmed in the fluorescent microscopy images (Figure 41), where several isolated polymer coalescences were observed. These results demonstrated the poor compatibility between the rPE samples and asphalt binders tested. The two compatibilizers evaluated in the study did not improve the storage stability of rPE modified binders.

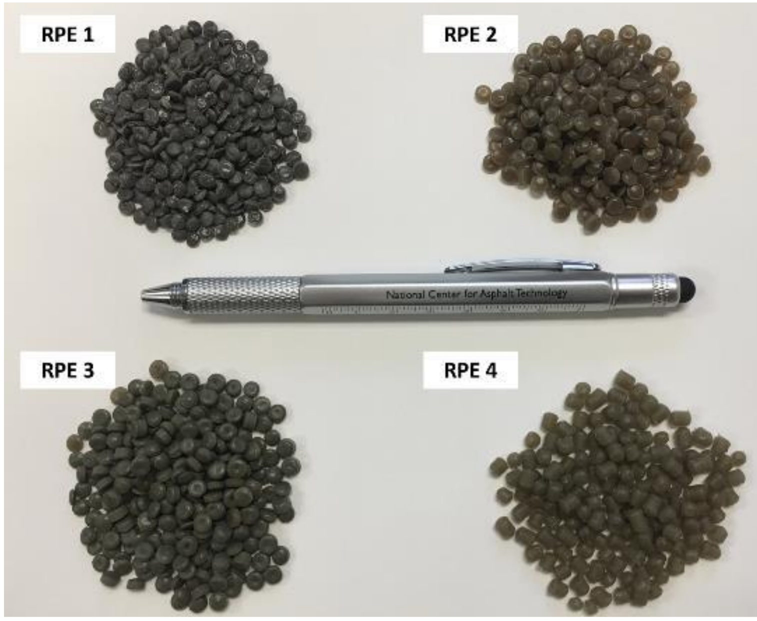


Figure 40. rPE Pellet Samples Used for Asphalt Modification (Yin and Moraes, 2018)

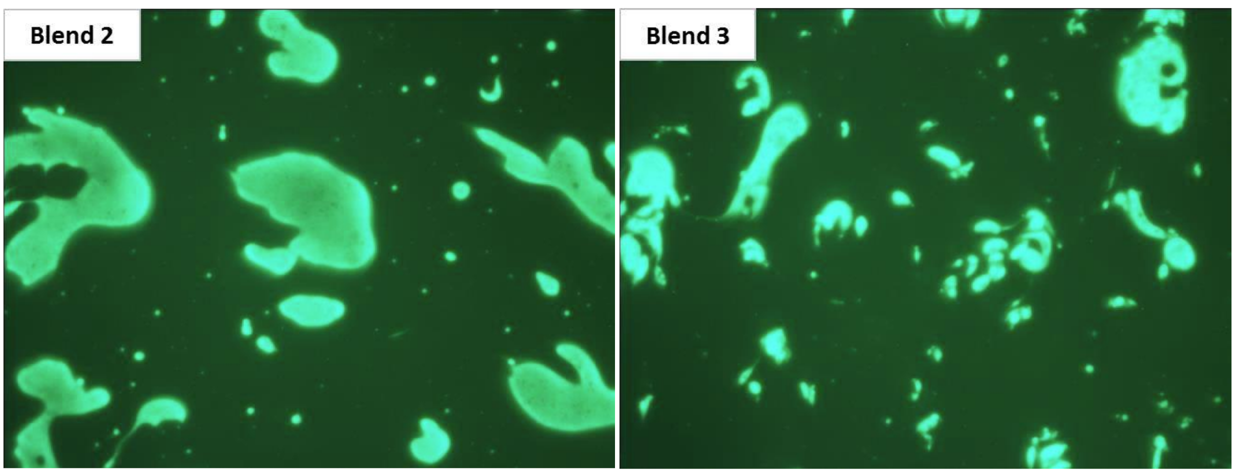


Figure 41. Fluorescent Microscopy Images of Two rPE Modified Binders (Yin and Moraes, 2018)

A follow-up study was conducted to investigate the use of additional compatibilizers and lower rPE dosages to mitigate the phase separation of rPE modified binders. Three compatibilizers were evaluated; the first one was an ethylene-based reactive elastomeric terpolymer, which was expected to act as a steric stabilizer in rPE modified binders. The second one was a semi-crystalline polyolefin additive that had been successfully used to disperse crumb rubber in asphalt binder and had the potential to enhance the interaction between rPE and asphalt binder via crosslinking reactions. The third one was an organic polymer additive consisting of polar and non-polar groups with affinity for asphalt binder and rPE, respectively. In this follow-up study, only one PG 58-28 binder and two rPE samples (Samples 2 and 3 in Figure 40) were tested. The dosage of rPE used varied from 2 to 5 percent by weight of asphalt binder. Each compatibilizer was added at two or three dosages following the material suppliers' recommendations. The same blending and testing procedures used in the previous study was followed. Test results showed that the three compatibilizers did not mitigate the phase separation of modified binders containing 5 percent rPE. However, adding an ethylene-based elastomeric reactive terpolymer greatly improved the dispersion of rPE in asphalt binder. Modified binders containing 2 and 3 percent rPE passed the specified storage stability requirement, while those at higher dosages failed. The addition of an ethylene-based elastomeric reactive terpolymer accommodated the use of 4 percent rPE for asphalt modification without failing the storage stability requirement.

"This Company is Using Recycled Plastic Milk Bottles to Repave Roads in South Africa" by E. Reynolds in *CNN Business – Innovate Africa* at https://www.cnn.com/2019/10/30/business/plastic-roads-in-south-africa-intl/index.html, 2019.

Authors	E. Reynolds (CNN Business)
Sponsor	Not applicable
Plastic Type	Recycled High-density Polyethylene (HDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	Not Specified
Scope	Field Project

This newsletter article discusses the successful completion of the first asphalt paving project using asphalt binders modified with recycled plastic milk bottles in South Africa. The project was a 400-meter road in KwaZulu-Natal (KZN) province on the east coast (Figure 42), which was commissioned by the KZN Department of Transport and constructed by Shisalanga Construction. Recycled milk bottles were collected and processed into high-density polyethylene (HDPE) pellets at a local recycling plant. The dosage of plastic pellets used was 6 percent by weight of asphalt binder. At this dosage, every ton of asphalt mixture contained roughly 118 to 128 two-liter milk bottles. Shisalanga Construction claimed that the production of plastic modified mixtures produced fewer toxic emissions than traditional asphalt mixtures and that asphalt mixtures after plastic modification were more durable in terms of resistance to fatigue and moisture damage. Shisalanga Construction has also proposed to the South Africa National Roads Agency for a 200-ton paving project on the country's main N3 highway between Durban and Johannesburg.

Figure 42. Photos of the First Asphalt Paving Project Using Asphalt Binder Modified with Recycled Bottles in South Africa (Reynolds, 2019)

"Use of Plastic Wastes from Greenhouse in Asphalt Mixes Manufactured by Dry Process" by J.E. Martin-Alfonso, A.A. Cuadri, J. Torres, M.E. Hidalgo, and P. Partal in *Road Materials and Pavement Design*, 2019.

Authors	J.E. Martin-Alfonso, A.A. Cuadri (Universidad de Huelva, Spain), J. Torres, M.E. Hidalgo (Eiffage Infraestructuras, Spain) and P. Partal (Universidad de Huelva, Spain)
Sponsor	European Union
Plastic Type	Recycled Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: 10 Percent by Weight of Asphalt Binder Dry Process: 0.5, 1, and 3 Percent by Weight of Aggregate
Scope	Laboratory Mixture Testing

This study assessed the applicability of recycled LDPE as a modifier of asphalt mixtures manufactured by a dry process. Asphalt binders with 15/25, 20/30, 35/50, 50/70, 70/100 and 500 penetration grades were used. The recycled LDPE was obtained from greenhouses used in agriculture and had a melting point of 109°C, specific gravity of 0.935, and melt flow index of 0.54 g/10 min. A recycled mineral lubricating oil was evaluated as a compatibilizer agent to prepare modified LDPE polymers at different LDPE percentages (71.2, 72.2, and 89.2 percent by weight). Test results indicated that the use of additives consisting of recycled LPDE previously swollen by mineral oil or asphalt was a promising way of reducing the mixing time, improving the waste plastic incorporation into asphalt mixtures through a dry process. Among the additives tested, 72.2 percent recycled LDPE modified with 27.8 percent mineral oil was the most effective in reducing long-term aging of the asphalt binder. Binders formulated with recycled polymer, regardless of the base binder used, exceeded the limit viscosity of 3 Pa.s. However, the results obtained from mixture performance testing indicated that compaction could still be performed when recycled LDPE was added using a dry process. Adding 0.5 percent recycled LDPE improved the moisture sensitivity and rutting resistance of asphalt mixtures. The addition of recycled LDPE also considerably improved the moisture sensitivity and fatigue resistance of high modulus asphalt mixtures. Conversely, rutting resistance and stiffness decreased when compared to the control mixture, but still met the agency requirements. However, adding recycled LDPE using the dry process reduced the air voids of porous asphalt mixtures. Finally, LDPE modified porous mixtures did not perform as well as the styrene-butadiene-styrene (SBS) modified mixture in terms of overall durability and fatigue resistance.

“Using Waste Plastics in Road Construction” by M. Sasidharan, M. Eskandari Torbaghan and M. Burrow in *Helpdesk Report K4D*, 2019.

Authors	M. Sasidharan, M. Eskandari Torbaghan and M. Burrow (University of Birmingham, United Kingdom)
Sponsor	Unknown
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Literature Review

This study performed a review of examples of waste plastics being used in road construction in a few case studies in several countries. The author stated that, “While roads constructed using waste plastics have shown good longevity and pavement performance to date, the first roads constructed using this technology are only about ten years old, so long-term outcomes are not yet clear. This review did not find any evidence discussing the maintenance of roads constructed using waste plastics.”

- India: The study indicated that India has promoted the use of waste plastic in bituminous mixes for the construction of its national highways and rural roads and has approved it as a default mode of periodic renewal with asphalt mixtures for roads within 50 km periphery of urban areas with more than 500,000 population. Since 2002, waste plastic has been used to construct more than 2,500 km of roads, which were reportedly functioning well without potholes, raveling, or rutting up to ten years later.
- United Kingdom: The study indicated that the UK government recently announced an investment of £23 million into plastic road technologies by setting up real-world tests across eight local authorities. The study also indicated that MacRebur (a UK based company) products are the only technology for road construction using waste plastic, which has made it to global commercial use.
- Ghana: The study indicated that a Ghana based plastic recycling company, NelPlast Ghana Ltd, produces pavement blocks from waste plastic. These pavement blocks have been approved by Ghana’s Ministry of Environment, Science, Technology and Innovation, and have been used to construct a road section in Accra.
- Netherlands: The study indicated that a 30-meter cycle path entirely built from prefab, modular, and hollow blocks manufactured from recycled plastic is operational in the Zwolle municipality in the Netherlands. A second such bicycle path is under construction in the Steenwijkerland municipality. The concept was developed by a consortium of KWS (a VolkerWessels company), Wavin and Total, who are currently working on the development of plastic roads for wider applications.

Regarding the construction methods, the study highlighted that asphalt mixtures using waste plastic for road construction could be manufactured using either a ‘dry’ process or a ‘wet’ process (Figure 43). The dry process is considered to be simple, economical and environmentally friendly, while the wet process requires more investment and machinery, and hence, is not commonly used. In the dry process, the processed waste plastic is shredded and added to the hot aggregate (in Figure 43, when lines a, b and d are opened, keeping c and e closed). Several existing studies indicated that the percentage of shredded waste plastic in asphalt mixtures was typically between 5 to 10 percent by weight of asphalt binder, with 8 percent being recommended as optimum percentage. In the wet process, the processed waste plastic in powder form is added to the hot asphalt (in Figure 43, when lines c and e are opened, and a, b and d are closed).

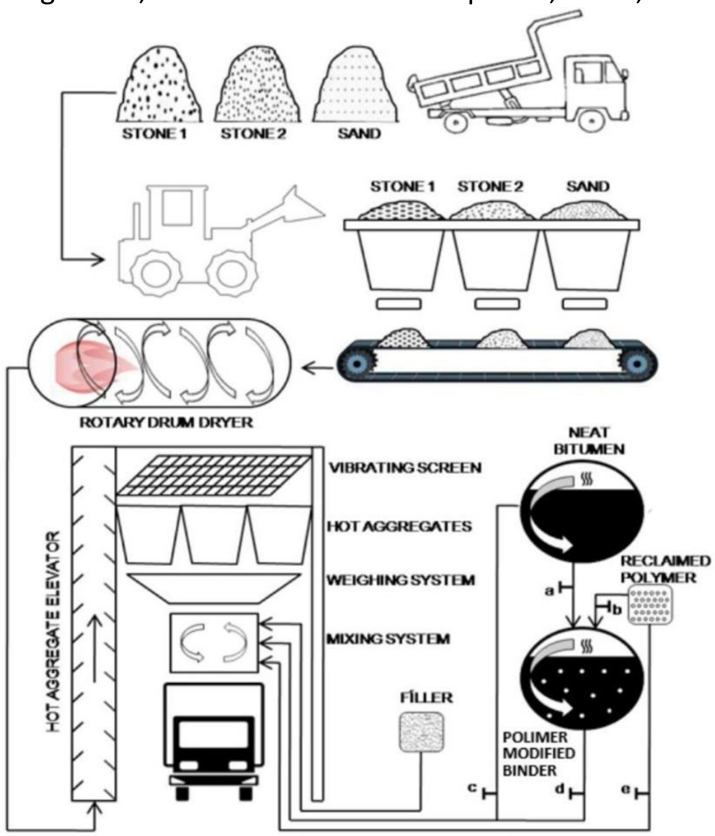


Figure 43. Sketch of the Wet Process and Dry Process of Adding Recycled Plastics in an Asphalt Plant (Sasidharan et al., 2019)

Regarding health and environmental hazards, the study indicated two chemical hazards associated with the application of waste plastic within road construction: leaching of toxic components during the cleaning process and generating hazardous chlorine-based gases during the road construction process. The study highlighted the importance of collecting and sorting waste plastics, suggesting that only the following types of waste plastics can be used for road construction: films (carrier bags, disposable cups) of thickness up to 60 microns (polyethylene, polypropylene, and polystyrene), hard foams (polystyrene) and soft foams (polyethylene and polypropylene) of any thickness, and laminated plastics of thickness up to 60 microns.

“Viability of Using Recycled Plastics in Asphalt and Sprayed Sealing Applications” by C. Chin and P. Damen as an *Austroads Publication (No. AP-T351-19)*, 2019.

Authors	C. Chin and P. Damen (Austroads, Australia)
Sponsor	Austroads
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Literature Review

This report summarizes the findings of a literature review on the use of recycled plastics in asphalt and sprayed sealing applications. The review included existing studies on the laboratory evaluation of asphalt binders and mixtures modified with recycled plastics and case studies of asphalt paving projects using plastics modified asphalt mixtures. The report identifies two approaches of adding recycled plastics into asphalt mixtures: dry process and wet process. In the dry process, recycled plastics are added directly into the mixture. In the wet process, recycled plastics are added into asphalt binder prior to being mixed with the aggregates. The dry process is generally recommended for recycled plastics with a high melting point while the wet process is commonly used for those with a low melting point. When added into asphalt mixtures, recycled plastics are expected to act as either aggregate extender (or replacement), asphalt extender, or asphalt modifier. Table 9 provides a partial list of field trials referenced in the report. A review of existing information seems to indicate that adding recycled plastics generally has an overall positive impact on the engineering properties of asphalt binders and mixtures and the short-term performance of asphalt pavements. Nevertheless, further research efforts are needed to validate these performance benefits through third-party assessments and public scrutiny and to monitor the long-term performance of existing field trials.

Table 9. A Partial List of Field Trials Referenced in the Report (Chin and Damen, 2019)

Country*	Type of Recycled Plastics Used	Roadway Application
Australia	Proprietary products from MacRebur, Downer EDI, Alex Fraser, and Fulton Hogan	City street
New Zealand	Proprietary products from Fulton Hogan	Airport’s fire station
Netherlands	PlasticRoad technology (prefabricated and lightweight modular pieces made of recycled plastics)	Bicycle track
Canada	Proprietary products from GreenMantra	City street
India	Shredded waste plastic (polymer makeup unknown)	Rural road, city street, and national highway
*Note: *Other countries cited in the report include Indonesia, Thailand, Saudi Arabia, and Ghana; however, only little information is provided about these field trials.*		

Based on the literature review, the report identifies several major concerns related to the use of recycled plastics in asphalt, including potential occupational health and safety hazards, release of microplastics, the future recyclability of asphalt mixtures modified with recycled plastics, compatibility and storage stability of plastics modified asphalt binders, and the material's life cycle sustainability. The report also calls for the need of developing a broad Australian framework on the use of recycled and alternative materials (including recycled plastics) in roadways. To that end, development and implementation of a performance related/based specification is highly recommended. Different from a prescriptive specification, a performance related/based specification emphasizes the end-product testing based on desired level of performance criteria, which is expected to provide producers with more flexibility in using innovative materials and technologies. Finally, the report recommends conducting additional research to develop a better understanding of the benefits and challenges of recycling plastics in asphalt and sprayed sealing applications. A list of relevant research and development activities are proposed and prioritized.

“Waste Plastic as Additive in Asphalt Pavement Reinforcement: A Review” by N.S. Mashaan, A. Rezagholilou, and H. Nikraz in *18th AAPA International Flexible Pavements Conference*, 2019.

Authors	N.S. Mashaan, A. Rezagholilou, H. Nikraz (Curtin University, Australia)
Sponsor	Australian Government Research Training Program, Australia
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Literature Review

This review paper focuses on asphalt mixtures containing waste plastic materials, incorporated through both the dry and wet processes. The paper states that the annual consumption of plastic has increased from about 5 million to 100 million tons globally within the second half of the last century; therefore, a well-managed reuse of waste plastics can offer significant economic and environmental benefits. Because asphalt pavements are subjected to heavy loads, heavy traffic, frequent stresses and various climactic and environmental conditions, an additive is often incorporated into the binder and/or mixture to achieve desired performance properties. The choice of the additives depends on various factors, such as construction ability, cost, and expected performance. Using waste plastic as an additive for asphalt modification or mixture reinforcement has the potential to improve pavement performance in terms of resistance to rutting, fatigue, and moisture damage. The paper provides a list of recycled plastic polymers that have been used as additives for asphalt pavement construction, including low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyethylene terephthalate (PET), and polystyrene (PS) (Table 10). Based on the findings of existing studies, adding 4 percent HDPE (by weight of asphalt binder) via the wet process seemed to be most effective in improving mixture stiffness and rutting resistance. Other researchers had also recommended the use of up to 6 to 8 percent PET (by weight of asphalt binder) via the dry process to improve the fatigue life and long-term performance of asphalt pavements. From the environmental point of view, existing studies suggested that recycling disposable plastics, or those that would need to be discarded after a lifetime, could yield several benefits as follows: preservation of limited natural resources, reduction of energy consumption, reduction of disposed and discarded solid waste, and reduction of carbon-dioxide (CO_2), sulphur-dioxide (SO_2), and nitrogen-oxide (NO) emissions. *[Commentary: these benefits are just assumptions which have not been quantified.*]

Table 10. Various Types of Plastics Used as Additives for Asphalt Pavement Construction (Mashaan et al., 2019)

Authors	Type of Plastic	Shape, Size and Dosage	Specifications
Ahmadinia et al. 2011	Waste PET	Chips/shredded, 1.18mm 2%, 4%, 6%, 8% and 10%	Specific gravity: 1.390
Casy et al. 2008	Waste PP, HDPE, and LDPE	Mulch PP, powder HDPE & LDPE 2%, 3%, 4% and 5%	Melting point: 131˚C (HDPE), 110˚C (LDPE)
Awwad & Shbeeb 2007	Waste HDPE and LDPE	Grinded and not grinded, 2-3mm 6%, 8%,10%, 12%, 14%, 16%, and 18%	Melting point: 125˚C (HDPE), 110˚C (LDPE) Specific gravity: 0.950 (HDPE), 0.920 (LDPE)
Al-Hadidy & Tan 2009	LDPE	Gridded to powder	Melting point: 113.2˚C Specific gravity: 0.921 Tensile strength: 10 MN/m^2
Zoorbo & Suparma 2000	Waste LDPE	Pellet, 5.00-2.36mm	Melting point: 140˚C Specific gravity: 0.920 Softening point: 120 ˚C
Kamada & Yamada 2002	Waste PP and PET	Pellet	Specific gravity: 0.921 (PP), 0.900 (PET)
Hinislioglu & Agar 2004	Waste HDPE	Powder, 2mm 4%, 6% and 8%	Specific gravity: 0.935
Ho et al. 2006	Waste PE and LDPE	PE: wax LDPE: pellet and shredded 2-4%	Not available
Attaelmana et al. 2011	HDPE	Pellet 1%, 3%, 5% and 7%	Melting point: 149˚C Specific gravity: 0.943 Tensile strength: 3 MPa
Vansudevan et al. 2012	Waste PE, PP and PS	Foam/powder 5%,10%,15% and 20%	Softening point: 120-210˚C
Modarres et al. 2014	Waste PET	Chips/crushed, 0.425-1.18mm 2%, 4%, 6%, 8% and 10%	Not available
Khan et al. 2016	Waste LDPE and HDPE	Powder, 0.15-0.75 mm 2%, 4%, 8% and 10%	Specific gravity: 0.922 (LDPE), 0.961 (HDPE) Softening point: 95˚C (LDPE), 127˚C (HDPE)

“Laboratory Evaluation of Asphalt Containing Recycled Plastic as a Bitumen Extender and Modifier” by G. White and C. Magee in *Journal of Traffic and Transportation Engineering 7*, 2019.

Authors	G. White and C. Magee (University of the Sunshine Coast, Australia)
Sponsor	Unknown
Plastic Type	Proprietary Products from MacRebur
Plastic Addition Method	Wet Process
Plastic Dosage	6% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

Low melting point plastics were used in this study to evaluate the effects of recycled plastics on the modification of asphalt binders. Asphalt binder and mixture samples containing recycled plastics were tested and compared to control samples. A 14 mm maximum-sized dense graded asphalt mixture and four different asphalt binders were used in this research. C320 was a conventional, unmodified binder (similar to 50/70 penetration grade). M1000 was a multi-grade binder modified with polyphosphoric acid. MacRebur’s commercial recycled plastic products, MR6 and MR10, were added to a conventional, unmodified binder (C170 – comparable to 80-100 penetration grade) at a dosage rate of 6% by weight of asphalt binder. MR6 was intended to produce asphalt mixtures with high stiffness and resistance to deformation, while MR10 was intended to produce asphalt mixtures with high fracture resistance. The binder content of the mixtures was set at 4.9%. Each binder sample was tested for viscosity at 60°C, softening point, and torsional recovery at 25°C. Mixture properties investigated in this study included volumetrics, Marshall properties, resilient modulus, dynamic modulus, fatigue life, wheel track rutting, and tensile strength ratio (TSR).

Statistical analysis of the performance test results indicated that recycled plastics had significant effects on the asphalt binder and mixture properties. Binder resistance to flow, asphalt workability, and resistance to deformation increased due to the addition of recycled plastics. However, adding recycled plastics reduced the mixture’s moisture damage resistance but did not remarkably change its fracture resistance. In addition, the MR6 modified binder had similar properties as M1000 (acid-modified multi-grade binder) but with generally better properties than the MR10 modified binder. Finally, the study recommended additional studies to further evaluate moisture damage and explore the dry method of adding recycled plastics in asphalt mixtures.

“Recycled Waste Plastic Modification of Bituminous Binder” by G. White and G. Reid in the *7th International Conference on Bituminous Mixtures and Pavements,* 2019.

Authors	G. White (University of the Sunshine Coast, Australia) and G. Reid (MacRebur, United Kingdom)
Sponsor	Unknown
Plastic Type	Proprietary Products from MacRebur
Plastic Addition Method	Wet Process
Plastic Dosage	4, 6, and 8% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

In this study, two commercial waste plastic products from MacRebur (as shown in Figure 44 and Figure 45) were added to the asphalt binder for modification. Samples with these additives were tested for the British binder specification properties and high-temperature PG grade based on the dynamic shear rheometer (DSR) $|G^*|/\sin(\delta)$ parameter (ASTM D6373) and the multiple stress creep and recovery (MSCR) (ASTM D7405) test results. For the UK specification, an unmodified 100/150 penetration grade binder and the same binder with 6% (by weight of asphalt binder) of the MacRebur products, MR6 and MR10, were tested. For the high-temperature PG grading, 50/70 and 100/150 penetration grade binders modified with 4, 6, and 8% of MR6 and MR10 were tested.

The results of the UK specification testing indicated that the penetration grade was reduced significantly by adding 6% of both MR6 and MR10 to the 100/150 penetration grade binder. Additionally, the softening point of the binders increased due to the addition of MR6 and MR10. Force ductility was increased more significantly with MR10 compared to MR6. The results of the high-temperature PG tests indicated that MR6 and MR10 similarly improved the rheological properties of the binders similar to those of a conventional polymer modified binder. Based on the results, the optimum dosage of the MacRebur products was determined to be 6% by weight of asphalt binder. Moreover, this study concluded that MR6 was plastomeric with limited recovery capacity, while MR10 was elastomeric with less deformation resistance than MR6. Furthermore, the study indicated that MR6 generally resulted in modified binders with higher PG grades than MR10. The result also indicated that the MR10 modified binders were generally more temperature sensitive than the MR6 modified binders as well as the other conventional polymer modified binders. Additionally, this study showed that asphalt binders containing MR6 had higher fracture toughness than those modified with MR10. Finally, the study recommended future research to compare the wet and dry methods of adding recycled plastics and evaluating the effects of waste plastics’ pellet size, shape, and density on the asphalt binder and mixture properties. The study also suggested economic and environmental evaluations of waste plastics for future research.

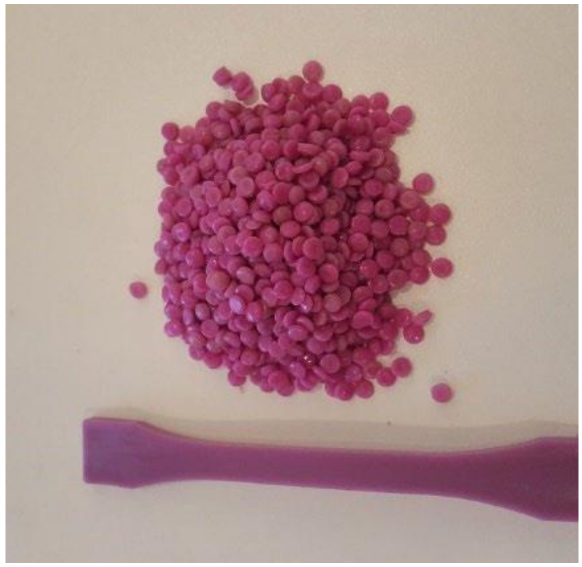


Figure 44. MR6 Pellets (White and Reid, 2019)


Figure 45. MR10 Pellets (White and Reid, 2019)

“Safety and Sustainability in Road Construction. Study of the Use of Recycled Plastics to Reduce Rutting in Asphalt Mixtures (Seguridad y Sustentabilidad en la construcción de carreteras. Estudio del empleo de plásticos reciclados para la reducción del ahuellamiento en mezclas asfálticas)” by M.L.C. Casaux, F. Martinez, M. Balige, and A. Berardo, 2019.

Authors	M.L.C. Casaux, F. Martinez (Universidad Nacional de Rosario, Argentina), M. Balige, and A. Berardo (Asfaltos. Ciudad de Buenos Aires, Argentina)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene
Plastic Addition Method	Dry Process
Plastic Dosage	Not Specified
Scope	Laboratory Mixture Testing

In this study, eight mixtures were evaluated in the laboratory including two control mixtures [i.e., CA30 (typical dense-graded mixture in Argentina) and AM3 (polymer modified mixture)], four CA30 mixtures containing waste polyethylene (PE) in flake, pellet, film, and micronized forms, and two CA20 mixtures containing micronized and pelletized waste polyethylene. All recycled plastics were incorporated directly into the asphalt mixture following the dry process. Laboratory tests included the dynamic modulus, wheel tracking, and mixture penetration (static) tests. Preparation of the mixtures with waste polyethylene plastics involved heating aggregates and asphalt binder, adding plastics (at room temperature) to hot aggregates, mixing both materials, adding asphalt binder, keeping the mix for temperature homogenization in an oven for half an hour, remixing and compacting mixture specimens. This research indicated that the mixtures obtained from this technique showed good workability, especially as the size of the recycled plastics is reduced, as is the case with micronized waste polyethylene. Overall, the test results indicated that adding waste polyethylene improved the stiffness and permanent deformation resistance of asphalt mixtures. Specifically, the polyethylene modified CA30 mixtures had similar permanent deformation as the AM3 mixture.

"The Effect of Low-Density Polyethylene Addition and Temperature on Creep-recovery Behavior of Hot Mix Asphalt" by M. Mazouz and M. Merbouh in *Civil Engineering Journal*, 2019.

Authors	M. Mazouz and M. Merbouh (University of Tahri Mohammed, Algeria)
Sponsor	Unknown
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Dry Process
Plastic Dosage	5% by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the effects of low-density polyethylene (LDPE) on the creep-recovery behavior of asphalt mixtures. Shredded LDPE with particle size of 1 to 3 mm^2 (Figure 46) was added into the asphalt mixture via the dry process at a dosage of 5.0% by weight of asphalt binder. Asphalt mixtures with and without LDPE modification were tested in the four-point bending deformation device at 20°C and 50°C to characterize their creep and recovery properties. Test results indicated that using LDPE for binder modification reduced the creep deformation and residual deformation of the asphalt mixture. Furthermore, adding LDPE increased the mixture's instantaneous elastic deformation at 50°C. These results highlighted the potential of LDPE in improving the high-temperature rutting resistance of asphalt mixtures due to increased stiffness and elasticity.

Figure 46. Shredded LDPE from Waste Plastic Bags (Mazouz and Merbouh, 2019)

"Investigating the Mechanical Properties of Asphalt Concrete Containing Waste Polyethylene Terephthalate" by H. Taherkhani and M.R. Arshadi in *Journal of Road Materials and Pavement Design*, 2019.

Authors	H. Taherkhani and M.R. Arshadi (University of Zanjan, Iran)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	2, 4, 6, 8, and 10% by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study evaluated the mechanical properties of asphalt mixtures modified by waste polyethylene terephthalate (PET) at various sizes (Figure 47). The coarse-graded PET had a particle size of 1.18 to 2.36mm while the fine-graded PET had a particle size of 0.297 to 0.595mm. These PET particles were added directly into the mixture via the dry process at dosages ranging from 2 to 10% by weight of asphalt binder. Marshall mix design was used to prepare the mixture samples, which were tested with the Marshall Stability test, indirect tensile strength (ITS) test, and Dynamic Creep test (under stress level of 300 kPa at 40°C) for performance characterization. The Marshall stability test results indicated that adding PET increased the Marshall stability of asphalt mixtures. Asphalt mixtures containing more than 4.0% PET exhibited unacceptable moisture resistance in the ITS test. The dynamic creep test results showed that permanent deformation increased as the PET dosage increased, which indicated the detrimental impact of adding PET on the mixture's rutting resistance. In general, asphalt mixtures modified with fine-graded PET performed better than those containing coarse-graded PET. Finally, 2 to 4% of fine-graded PET was recommended for asphalt mixture modification.

Figure 47. Coarse and Fine PET Particles (Taherkhani and Arshadi, 2019)

“Information Related to the BRITE EURAM Project” by W. Tappeiner in *Email Communications*, 2020.

Authors	W. Tappeiner
Sponsor	Not Applicable
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Not Specified
Plastic Dosage	Not Specified
Scope	Laboratory Binder Testing, Laboratory Mixture Testing, Field Project

A four-year research project was conducted to evaluate the use of recycled polyethylene (PE) for asphalt modification from 1998 to 2002. The project was a collaboration between the European Community under the BRITE EURAM Program and five European companies. The primary objectives of this project were to improve the selection criteria of recycled PE for asphalt modification, explore the use of current laboratory tests for quality control of asphalt binders and mixtures modified with recycled PE, and compare the performance of asphalt binders and mixtures modified with virgin versus recycled PE. Raw materials evaluated in the project included 6 different sources of asphalt binders with 50-70 and 70-100 penetration grades, 44 grades of virgin PE [including linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), medium-density polyethylene (MDPE), and high-density polyethylene (HDPE)] from eight European producers, and 10 sources of recycled PE from four European countries. Figure 48 presents several recycled PE samples tested in the project.

A total of 288 different PE modified binder formulations were prepared and tested for softening point and Superpave performance grading. Upon completion of binder testing, the most promising PE modified binders were further evaluated through mixture performance testing. Two different asphalt mixtures were included: one dense-graded mixture and one gap-graded stone mastic asphalt (SMA) mixture. Each mixture was tested using the resilient modulus, indirect tensile strength, static and dynamic creep deformation, wheel-tracking, and cyclic axial compressive fatigue tests. The selection criteria of recycled PE for asphalt modification was developed based on gel permeability chromatograph, Fourier transform infrared spectroscopy, differential scanning calorimetry, and shear-rate dependent melt viscosity. The overall conclusion of the project was that when suitable selection criteria were applied, asphalt binders and mixtures modified with recycled PE could perform as well as those modified with virgin PE and provide satisfactory performance under a broad range of loading and temperature conditions. Detailed research findings and conclusions of the project, however, were not provided due to a confidentiality agreement. Upon completion of the project, a test section was constructed on the Autobahn A-62 in Saarland, Germany.

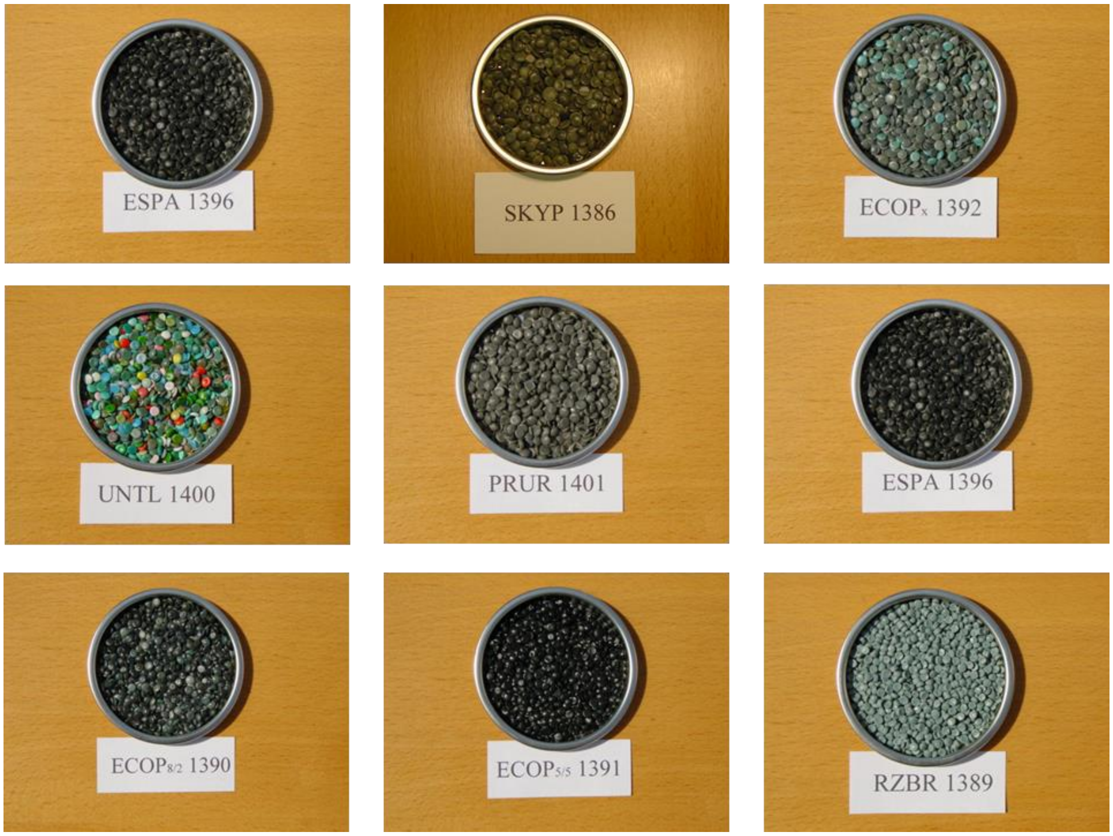


Figure 48. Recycled PE Samples in the BRITE-EURAM Research Project (Tappeiner, 2020)

“Welcome to Polyphalt Inc.” at http://www.polyphalt.com/, accessed on January 20, 2020.

“Licensing Process Technology for Polymer Modified Bitumen” Accessed on January 20, 2020.

“Ontario Asphalt Technology Takes on the World” Accessed on January 20, 2020.

Authors	Polyphalt, Inc. (Canada)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process (Polyphalt®)
Plastic Dosage	Not Specified
Scope	Product Introduction

This website lists two proprietary asphalt technologies from Polyphalt®, Inc., that allow the use of virgin or recycled polyethylene for asphalt modification: *SPx™* and *EPx™*. The development of these technologies started in the late 1980s at the University of Toronto, Canada. *SPx™* is claimed to be the world’s first process for stabilizing plastics in asphalt binder. In this process, a steric stabilizer made of polymers with a high degree of elasticity and excellent adhesive properties is utilized to mitigate the phase separation of plastics from asphalt binder. Figure 49 illustrates the enhanced morphology of Polyphalt® *SPx™* binders relative to traditional polyethylene modified binders. The polymer stabilizer also acts as an emulsifier creating polyethylene particles one micron or less, which contributes to superior storage stability. *EPx™* takes advantage of *SPx™* and reacts polyethylene and styrene-butadiene-styrene (SBS) to form an interpenetrating copolymer network in asphalt binder, as shown in Figure 50. Asphalt binders modified with the EPx™ technology are claimed to provide superior toughness, high modulus, and elasticity. The commercial use of Polyphalt® technologies was based on licensing. About two decades ago, a dozen high-profile projects were constructed using Polyphalt® technologies in the United States, Canada, and Australia. Some of these projects were Yellowstone National Park’s Sylvan Pass, the main runway at the Spokane International Airport in Washington, California Speedway, and Sydney’s M-4 Motorway.

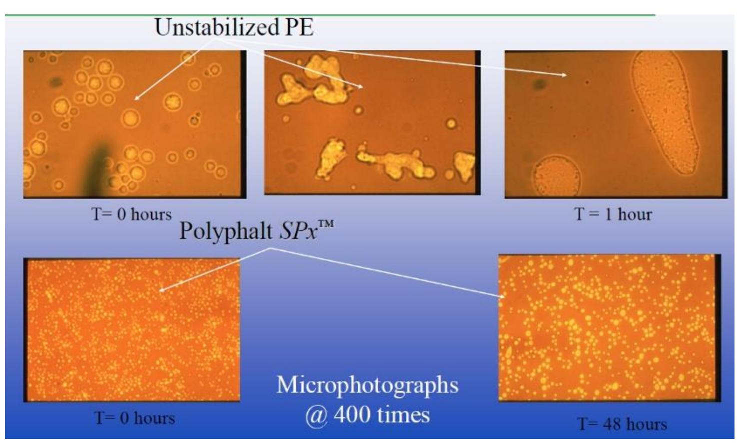


Figure 49. Enhanced Morphology Polyphalt® *SPx™* Binders versus Conventional Polyethylene Modified Binders (Polyphalt® Inc., 2020)

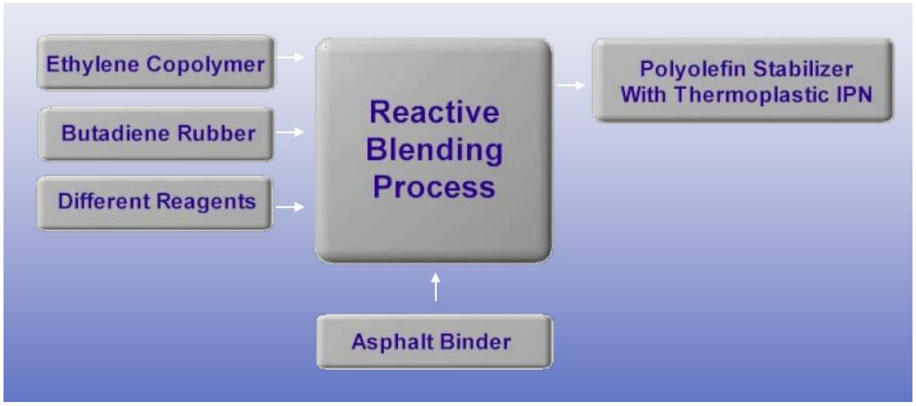


Figure 50. Polyphalt® *EPx*^{TM} Technology (Polyphalt® Inc., 2020)

“Recycled Plastic as Bitumen Modifier: The Role of Recycled Linear Low Density Polyethylene in the Modification of Physical, Chemical and Rheological Properties of Bitumen” by S. Nizamuddin, M. Jamal, R. Gravina, and F. Giustozzi in *Journal of Cleaner Production*, 2020.

Authors	S. Nizamuddin, M. Jamal, R. Gravina, and F. Giustozzi (RMIT University, Australia)
Sponsor	Unknown
Plastic Type	Recycled Linear Low-density Polyethylene (LLDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	3, 6, 9 and 12% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This research evaluated the properties of an asphalt binder modified with recycled linear low-density polyethylene (R-LLDPE). A R-LLDPE sample in powder form with a maximum nominal size of 600µm was added to a C320 binder at dosages of 3, 6, 9, and 12% by weight of asphalt binder via the wet process. The penetration, softening point, and penetration index tests were conducted to measure the binder physical properties. The thermogravimetric analysis (TGA), derivative thermogravimetry (DTG), and modulated differential scanning calorimetry (MDSC) tests were conducted to characterize the binder thermal properties. The viscosity, MSCR, and frequency sweep tests were conducted to evaluate the binder rheological properties. Additionally, the Fourier transform infrared spectroscopy (FTIR) test was used to characterize the chemical properties of the base and R-LLDPE modified binders.

Test results showed that R-LLDPE modified binders had increased viscosity and softening point, reduced penetration, and improved Penetration Index compared to the base binder. The viscosity increase was attributed to the low melting point and higher thermal stability of R-LLDPE and the complex internal structure during polymer and binder blending. The increased softening point and reduced penetration value of R-LLDPE modified binders indicated potentially better resistance to permanent deformation. The FTIR analysis showed that there was no significant difference between the base and modified binders in terms of their chemical properties. The MDSC results highlighted that increasing R-LLDPE dosage did not have a significant effect on melting temperature of the asphalt binder. The TGA and DTG analysis indicated that the weight loss during the test was primarily due to the base binder. Additionally, asphalt binders modified with lower R-LLDPE dosages had greater weight loss compared to those with higher R-LLDPE dosages. This difference could be due to the higher thermal stability of the R-LLDPE modified binder. R-LLDPE modified binders had enhanced rheological properties including a lower phase angle and higher complex shear modulus than the base binder. The improvement in the low- and intermediate-temperature rheological properties was not evident for 3% and 6% R-LLDPE, but was apparent at higher dosages. The multiple stress creep and recovery (MSCR) results indicated that R-LLDPE modified binders had significantly higher percentage recovery and lower J_{nr} values, indicating better rutting resistance at high temperatures compared to the base binder.

The authors noted that although adding higher dosages of R-LLDPE improved the rutting resistance of the asphalt binder, it caused a sharp viscosity increase at polymer loadings above 6%; therefore, dosages between 3 and 6% were recommended to have the best performance and sustainability. Finally, the study suggested future research to evaluate various kinds of waste plastics, additives, and different amounts of plastics for asphalt binder modification, as well as fume emissions associated with the use of recycled plastics in asphalt.

"A Review of Asphalt Modification Using Plastics: A Focus on Polyethylene" by E. Masad, K. L. Roja, A. Rehman, and A. Abdala, 2020

Authors	E. Masad, K. L. Roja, A. Rehman, and A. Abdala (Texas A&M University at Qatar, Qatar)
Sponsor	Unknown
Plastic Type	Polyethylene
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Literature Review

This article reviews the challenges in using polyethylene (PE) as an asphalt modifier. PE is categorized based on density into low density polyethylene (LDPE), high-density polyethylene (HDPE), and linear low-density polyethylene (LLDPE). Various plastics have been used in the past; however, the interest of PE recycling has recently increased because of the environmental and sustainability emphasis.

Performance of PE-modified mixtures depends on various factors, and properties of the polymer could affect the mixtures in different ways. For example, the nature and size of the polymer could have significant effects on the mixture's properties. In addition to polymer properties, binder properties and the blending method also affect the mixture properties. PE has been shown to increase binder stiffness. Various tests and research have shown that phase separation is a major issue for the wet process of adding PE since PE has low compatibility with asphalt binders due to differences in molecular structure, density, molecular weight, and viscosity of the components. Factors such as polymer dosage, polymer size, polymer properties, and binder grade need to be considered while using PE for asphalt binder modification. Adding additives could overcome the phase separation issue. This review notes that the chemical, thermal, microstructural, and mechanical properties of the PE-modified binder should be considered for performance characterization.

This research compares the dry and wet mixing methods to produce PE modified asphalt mixtures and concludes that although the dry process is easy to follow and does not need high shear to blend the polymer into asphalt binder, it may not be sufficient for the polymer to coat aggregates with uniform thickness. Moreover, the interaction between the polymer and asphalt binder cannot be easily determined for the dry mixing process; therefore, in most studies, researchers used the wet process of adding PE because it yielded better results for binder modification. Finally, the review notes that the optimum PE content recommended in most studies is between 3 to 6% by weight of asphalt binder.

"Recycling Waste Plastics in Roads: A Life-cycle Assessment Study using Primary Data" by J. Santos, A. Pham, P. Stasinopoulos, and F. Giustozzi in *Journal of Science of the Total Environment*, 2020.

Authors	J. Santos (University of Twente, the Netherlands), A. Pham, P. Stasinopoulos, and F. Giustozzi (RMIT University, Australia)
Sponsor	Unknown
Plastic Type	Not Specified
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: 2, 4, 6, and 8% by Weight of Asphalt Binder Dry Process: 2.5, 5, 10, and 20% by Weight of Aggregate
Scope	Environmental Impact Assessment

This study discussed the environmental effects from the production of recycled plastic pellets (RPP) and the use of RPP in asphalt mixtures to modify asphalt binders or replace natural aggregates. Moreover, this research compared the environmental impacts of RPP modified asphalt binders and mixtures versus those containing pure plastomers, such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), thermoplastic elastomers [styrene-butadiene-styrene (SBS)], and natural aggregates. The environmental impact analysis included both the dry and wet methods of adding RPP. For the wet method, 2, 4, 6, and 8% of RPP (by weight of asphalt binder) were added to the asphalt binder. For the dry method, 2.5, 5, 10, and 20% of RPP (by weight of aggregate) were added to the mixture by replacing the aggregates.

In the first part of this research, the four steps (collection, sorting, shredding, and pelletization) of the production of recycled plastic pellets were evaluated according to environmental impact categories. The potential environmental impact was found driven by the pelletization process due to its high consumption of electric energy.

In the second part of this research, asphalt binders modified with RPP and virgin polymers (SBS, LDPE, and HDPE) were evaluated for each environmental impact category. The study indicated that using RPP as an asphalt binder modifier could have significant environmental benefits compared to asphalt binders modified with virgin polymers. Despite the small amount of RPP used, the wet process is expected to be environmentally friendly, cost effective, and efficient in improving asphalt binder performance.

In the third part of this study, different percentages of RPP replacing natural aggregates were evaluated for the environmental impact categories. Results showed that although the low percent of RPP (2.5%) could increase the recycling rate without substantially affecting the ecosystem, replacing RPP with aggregates utilizing the dry method generally would not have remarkable environmental benefits and the economic impacts on asphalt mixtures would be negative since natural aggregates are much cheaper than RPP. The study recommended future research for a multi-attribute analysis that considers costs and mechanical performance in addition to the environmental factors.

"Laboratory Comparison of Wet-mixing and Dry-mixing of Recycled Waste Plastic for Binder and Asphalt Modification" by, G. White and F. Hall, 2020.

Authors	G. White and F. Hall (University of the Sunshine Coast, Australia)
Sponsor	Unknown
Plastic Type	Proprietary Products from MacRebur
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	6% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study compared the dry process and wet process of adding proprietary waste plastic products from MacRebur, MR6 and MR10, in asphalt mixtures. For the wet process, the waste plastic products were added into the asphalt binder and sheared for 15 minutes. For the dry process, the waste plastic products were added directly to the hot aggregates before mixing with the asphalt binder. The dosage of MR6 and MR10 was 6% by weight of asphalt binder. Mixture performance testing included the Marshall stability, deformation resistance, indirect tensile strength (ITS), moisture sensitivity, wheel tracking, and fatigue tests. Binder performance testing included the penetration, softening point, and elastic recovery tests.

The binder test results indicated that adding MR6 and MR10 decreased the penetration and increased the softening point of the asphalt binder. The mixture test results indicated that adding MR6 and MR10 significantly improved the deformation resistance of the asphalt mixture but did not impact its fatigue life or moisture susceptibility. The wet process and dry process did not yield asphalt binders with significantly different properties. Similar conclusions were also observed for the mixture performance test results except that the dry-process and wet-process modified mixtures exhibited different wheel tracking and tensile strength ratio (TSR) results. Finally, the authors suggested that using the dry process would be more accessible and could produce asphalt mixtures of more consistent quality compared to the wet process.

"Experimental Exploration of Influence of Recycled Polymer Components on Rutting Resistance and Fatigue Behavior of Asphalt Mixtures" by J. Zhang, H. Li, P. Liu, M. Liang, H. Jiang, Z. Yao, and G. Airey in *Journal of Materials in Civil Engineering*, 2020.

Authors	J. Zhang, H. Li, P. Liu, M. Liang, H. Jiang, Z. Yao (Shandong University, China), and G. Airey (University of Nottingham, United Kingdom)
Sponsor	Unknown
Plastic Type	Polyethylene (PE)
Plastic Addition Method	Dry Process
Plastic Dosage	0.2 and 0.3% by Weight of Asphalt Mixture
Scope	Laboratory Mixture Testing

This study examined the rutting and fatigue performance of asphalt mixtures modified with crumb rubber (CR) and polyethylene (PE). CR particles with a size of 0.4 to 0.8 mm were added into the asphalt binder using the wet process, while PE particles with a size of 2.0 to 3.0 mm were added to modify the mixture via the dry process. The dosages of CR particles were 15, 18, and 21% by weight of asphalt binder. The dosages of PE particles were 0.2% and 0.3% by weight of the mixture. The mix design used in this study consisted of a 70 penetration-grade asphalt binder and limestone aggregates. For mixture performance testing, the wheel tracking, uniaxial penetration [same as the California bearing ratio (CBR) test], and four-point bending beam fatigue tests were conducted to assess the performance properties of unmodified and CR-plus-PE modified mixtures. Test results demonstrated that adding PE and CR improved the rutting resistance and penetration strength of the asphalt mixture. The addition of PE had a detrimental impact on the fatigue resistance of the asphalt mixture, but this impact was counteracted by adding CR. Adding 21% CR and 0.2% PE yielded the modified mixture with the best overall performance properties and thus, was recommended as the optimum modification level.

“Performance Comparison of Waste Plastic Modified versus Conventional Bituminous Roads in Pune City: A Case Study” by A. Biswas, A. Goel, and S. Potnis in *Case Studies in Construction Materials*, 2020.

Authors	A. Biswas, A. Goel, and S. Potnis (National Institute of Construction Management & Research, India)
Sponsor	Unknown
Plastic Type	Not Specified
Plastic Addition Method	Not Specified
Plastic Dosage	8% by Weight of Asphalt Mixture
Scope	Field Project

This study evaluated the in-service performance of plastic-modified asphalt pavements by assessing their deterioration rate and rank of distress parameters using the analytic hierarchy process (AHP) model. Five traditional asphalt pavement sections and five plastic-modified pavement sections with similar cross-section and traffic conditions were included for evaluation. The plastic-modified pavement sections were constructed with asphalt mixes containing shredded waste plastic at a dosage of 8% by weight of the mixture. Various non-destructive pavement tests, including the Benkelman beam deflection (BBD) test, skid resistance test, and roughness test (by bump integrator), were conducted to determine the pavement deterioration parameters. Moreover, the pavement condition index (PCI) of these pavement sections were calculated according to the Indian road congress code (IRCC). The collected pavement performance data was also analyzed using the AHP model. Based on the collected pavement data and performance analysis results, the study concluded that adding recycled plastics delayed the deterioration rate of asphalt pavements. The study also recommended future research to consider various traffic, environmental, and geographical conditions when evaluating the impacts of adding recycled plastics on the performance of asphalt pavements.

"Compound Modification of Asphalt with Styrene-butadiene-styrene and Waste Polyethylene Terephthalate Functionalized Additives" by R.K. Padhan, Z. Leng, A. Sreeram, and X. Xu in *Journal of Cleaner Production*, 2020.

Authors	R.K. Padhan (Indian Oil Corporation Limited, Faridabad, India), Z. Leng (Hong Kong Polytechnic University, China), A. Sreeram (University of Texas at Austin, United States), and X. Xu (Hong Kong Polytechnic University, China)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Wet Process
Plastic Dosage	3.0 and 5.0% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the effects of adding recycled materials on the rheological and chemical properties of asphalt binders. In this regard, styrene-butadiene-styrene (SBS) and polyethylene terephthalate (PET) were used for binder modification via the wet process. This study included an unmodified binder with a penetration grade of 60/70, a 4% SBS modified binder, and two SBS-plus-PET modified binders. The polymer dosages of the hybrid modified binders corresponded to 4.0% SBS and 3.0% PET, and 4.0% SBS and 5.0% PET, respectively. All the binders were tested to determine their conventional physical properties using the penetration, softening point, viscosity, and storage stability tests, rutting and cracking resistance using the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests, as well as chemical properties using the Fourier transform infrared spectrometry (FTIR) and scanning electron microscope (SEM) tests.

Test results indicated that adding PET in general stiffened the SBS modified binder and improved its storage stability and rutting resistance. Furthermore, adding 3% PET improved the fatigue resistance of the SBS modified binder based on the DSR $|G^*|\sin(\delta)$ parameter. The FTIR and SEM results highlighted the development of chemical interactions between PET and SBS, which improved the performance properties of the modified binder. Based on these results, the study concluded that binder modification with PET and SBS was more effective in improving the performance properties of asphalt binders compared to using SBS alone for binder modification.

"A Synthesis on the Effects of Two Commercial Recycled Plastics on the Properties of Bitumen and Asphalt" by G. White in *Journal of Sustainability*, 2020.

Authors	G. White
Sponsor	Unknown
Plastic Type	Proprietary Products from MacRebur
Plastic Addition Method	Wet Process
Plastic Dosage	6% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study provided a synthesis on the impacts of two commercial recycled plastic additives (MR6 and MR10 from MacRebur) on the performance properties of asphalt binders and mixtures. The plastic additives were added into the asphalt binder via the wet process at a dosage of 6% by weight of asphalt binder.

As shown in Table 11, the binder performance test results indicated that adding MR6 and MR10 improved the binder's resistance to flow, elasticity, ductility, and performance grade. The mixture performance test results showed that adding these recycled plastic additives improved the rutting resistance of asphalt mixtures but did not have a significant impact on their resistance to fatigue cracking and moisture damage.

Table 11. Impacts of MR6 and MR10 on Asphalt Binder and Mixture Properties (White, 2020)

Property	Effect
Binder properties	
Resistance to flow	Significant increase in resistance to flow, based on penetration and viscosity
Elasticity and ductility	Incorporation of substantial elasticity and ductility that were negligible in the unmodified asphalt
Performance grading	Three (MR6) to four (MR10) grade increases based on the MSCR test protocol
Mixture properties	
Stiffness	Two- to three-fold increase across various mixture types, based on various measures of mixture modulus
Deformation resistance	Significant 65% (MR6) and 43% (MR10) reduction in wheel tracking rut depths for various mixture types
Crack resistance	No significant reduction in fatigue life or fracture prorogation resistance, using various test methods
Moisture damage resistance	No significant difference in resistance to moisture damage across various mixture types, based on the Lottman test

"Effect of Laboratory Aging on Moisture Susceptibility of Polymer-modified Bituminous Mixtures" by K.H. Ibrahim Al Helo, Z.I. Qasim, and M.A. Abdulhussein in *IOP Conf. Series: Materials Science and Engineering 737*, 2020.

Authors	K.H. Ibrahim Al Helo, Z.I. Qasim, and M.A. Abdulhussein (University of Technology, Iraq)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	1, 2, 3, and 5% by Weight of Asphalt Binder
Scope	Laboratory Mixture Testing

This study assessed the impacts of aging on the moisture susceptibility of polyethylene terephthalate (PET) modified asphalt mixtures. In this regard, PET was added into the asphalt mixture via the dry process at dosages of 1, 2, 3, and 5% by weight of asphalt binder.
Marshall stability and indirect tensile strength (ITS) test results indicated that adding PET increased the Marshall stability and moisture resistance of asphalt mixtures. Furthermore, the Marshall stability, ITS, and tensile strength ratio (TSR) results of both unmodified and PET modified mixtures increased as a result of mix aging. Based on these results, the study concluded that adding PET enhanced the mechanical properties of asphalt mixtures at both unaged and aged conditions. The study also recommended 5% as the optimum dosage of PET for modifying asphalt mixtures.

"Fracture and Mechanical Properties of Asphalt Mixtures Containing Granular Polyethylene Terephthalate (PET)"by A.S. Esfandabad, S.M. Motevalizadeh, R. Sedghi, P. Ayar, and S.M. Asgharzadeh in *Journal of Construction and Building Materials,* 2020.

Authors	A.S. Esfandabad, S.M. Motevalizadeh, R. Sedghi (Tarbiat Modares University, Iran), P. Ayar (Iran University of Science and Technology, Iran), and S.M. Asgharzadeh (Tarbiat Modares University, Iran)
Sponsor	Unknown
Plastic Type	Polyethylene Terephthalate (PET)
Plastic Addition Method	Dry Process
Plastic Dosage	30, 50, 70, and 100% by Weight of 2.36mm Aggregate Fractions
Scope	Laboratory Mixture Testing

This study investigated the fracture and mechanical properties of asphalt mixtures modified with granular polyethylene terephthalate (PET). Granular PET particles were added into the mixture to replace 2.36 mm aggregate fractions at different dosages: 30, 50, 70, and 100%. The PET modified mixtures were tested for moisture resistance using the indirect tensile strength (ITS) test, rutting resistance using the wheel tracking test, and fracture resistance using the semi-circular bending (SCB) test.

Test results indicated that although adding PET reduced the ITS values of asphalt mixtures, all of the PET modified mixtures had acceptable tensile strength ratio (TSR) values (> 80%). Adding granular PET improved the mixture rutting resistance in the wheel tracking test and this improvement was more pronounced at higher PET dosages. The SCB test results showed that all the PET modified mixtures had very similar fracture energy results as the unmodified mixture when tested at 0°C. At -20°C, the fracture energy results increased as the PET dosage increased from 30 to 70%, but then decreased as the dosage further increased to 100%. In comparing against the unmodified mixture, only the 30% PET modified mixture had lower fracture energy while the other modified mixtures at higher PET dosages had similar or higher fracture energy. Finally, the Weibull distribution analysis of the SCB test results showed that the probability of fracture failure increased significantly as the test temperature reduced from 0°C to -20°C. The study concluded that in general, adding PET increased the susceptibility of asphalt mixtures to fracture failure.

“Chemical and High-temperature Rheological Properties of Recycled Plastics-polymer Modified Hybrid Bitumen” by I.B. Joohari and F. Giustozzi in *Journal of Cleaner Production,* 2020.

Authors	I.B. Joohari and F. Giustozzi (RMIT University, Australia)
Sponsor	Unknown
Plastic Type	Recycled Linear Low-Density Polyethylene (RLLDPE), Ethylene-Vinyl Acetate (EVA), Low-Density Polyethylene (LDPE), Linear Low-Density Polyethylene (LLDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the thermal, chemical, and rheological properties of hybrid plastics-polymer modified binders containing 3.5% styrene-butadiene polymers (SBS) and various plastomers including recycled linear low-density polyethylene (RLLDPE), virgin low-density polyethylene (LDPE), virgin linear low-density polyethylene (LLDPE), and virgin ethylene-vinyl acetate (EVA) at a dosage of 2% by weight of asphalt binder as shown in Figure 51. A C170 (comparable to 70/100 penetration grade) was used as the base asphalt binder for hybrid plastics-polymer modification. Sulphur was also used to assess the chemical crosslinking effect. Conventional asphalt binder tests, modulated differential scanning calorimetry (MDSC), Fourier-transform infrared spectroscopy (FTIR), and frequency sweep test were conducted.

The results indicated that replacing virgin plastomers with RLLDPE yielded modified binders with increased softening point and decreased penetration value. The MDSC test results showed no considerable difference in the chemical composition structure and thermal behavior of virgin and recycled LLDPE. The FTIR analysis did not identify any major variations between the SBS-plus-RLLDPE modified binder versus asphalt binders modified with SBS and virgin plastomers. The DSR frequency sweep test results indicated that the SBS-plus-RLLDPE modified binder was stiffer and had better elastic response at high temperatures than the SBS-plus-virgin LLDPE modified binder. Adding 0.1% sulphur enhanced the rheological properties of the hybrid modified binders. Finally, the authors concluded that recycled polyethylene, specifically RLLDPE, yielded modified binders with better performance properties through its combination with SBS compared to other virgin plastomers.

Figure 51. Virgin LLDPE (Left) and RLLDPE (Right) (Joohari and Giustozzi, 2020)

"Use of Recycled Plastic in Local Roads in Regional Areas" by D.Y.H. Lin, K.J. Dong, H. Bakshi, R.Y. Yi, and P. Kumar in *Institute of Public Works Engineering Australasia Report*, 2020.

Authors	D.Y.H. Lin, K.J. Dong, H. Bakshi, R.Y. Yi, and P. Kumar (Institute of Public Works Engineering Australasia, Australia)
Sponsor	Institute of Public Works Engineering Australasia, Australia
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Technical Guidance

This report provides information about classification, consumption, recovery, and recycling processes of plastics for evaluating the feasibility of using them as asphalt binder or asphalt mixture modifiers in road construction. The report discusses different types of recycled plastics, including polyethylene terephthalate (PETE), high density polyethylene (HDPE), vinyl (V), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), etc. The most plastic consumption in Australia is related to HDPE. Shredding, washing, melting, and palletization are the main steps of the plastic recycling process. The report identifies several benefits of using plastics in road construction, which includes reduced needs for virgin materials, energy consumption, and removal from landfills.

The report discusses the dry and wet process for adding recycled plastics into asphalt mixtures. The general approach is to add recycled plastics with a high melting point via the dry process and add recycled plastics with a low melting point via the wet process. The report summarizes various research studies related to using recycled plastics as asphalt binder or asphalt mixture modifiers and evaluating their impacts on the performance properties of the resultant modified asphalt binders and/or mixtures. Life cycle assessment (LCA) has been conducted in various research to evaluate the environmental effects of using recycle plastics in road construction. The report highlights climate change (CC), ozone depletion (OD), acidification (AP), and eutrophication (EU) as the most used analyses in this regard. Several research studies conducted the life cycle cost analysis (LCCA) and concluded that using waste plastics for road construction would be cost-effective in the future.

The authors also overview and compare general properties, benefits, and justifications for the wet process and dry process of using recycled plastics in road construction. Specifically, the report evaluates commercial products available in Australia. The report uses multi-criteria analysis and ranks the different processing methods by considering five main criteria, including structural performance, environmental impact, safety and risks, life cycle, and awareness/understanding. The analysis results indicate that the wet process is more successful and promising than the dry process because it scores higher for the five parameters considered in the multi-criteria analysis. Furthermore, the dry process is considered to have a higher risk of generating micro-plastics because it involves a significantly higher amount of plastic waste into asphalt mixtures than the wet process.

The authors also identify several challenges associated with the use of recycled plastics for road construction, including health and safety, micro-plastics, reuse of polymer modified binders, plastic compatibility, and storage stability. Results from reviewing various research demonstrates that toxic emissions, leaching hazards, and worker health are significant issues that should be addressed. The report indicates that the release of micro-plastics can be prevented in a plastic road when waste plastics are heated to the appropriate temperatures and quality control standards are strictly followed. Moreover, the impact of micro-plastics generated from polymer modified binder on the environment is less than micro-plastics generated from tires. The laboratory storage stability test results show that among polyethylene (PE), PP, polyvinyl chloride (PVC), and ethyl vinyl acetate (EVA), only PE and EVA have demonstrated the capacity to remain stable without the use of compatibilizer additives.

"Analysis of Waste Polyethylene (PE) and its By-products in Asphalt Binder" by M.R. Kakar, P. Mikhailenko, Z. Piao, M. Bueno, and L. Poulikakos in *Journal of Construction and Building Materials*, 2021.

Authors	M.R. Kakar, P. Mikhailenko, Z. Piao, M. Bueno, and L. Poulikakos (Swiss Federal Institute of Technology in Zurich, Switzerland)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene
Plastic Addition Method	Wet Process
Plastic Dosage	5% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study investigated the suitability of using recycled high-density polyethylene (HDPE) from packaging materials as an asphalt binder additive. The recycled HDPE was obtained from InnoRecycling AG (Switzerland) and was added to a 70/100 penetration grade binder in two forms: pellet (density equal to 0.945 g/cm3, particle size below 2 mm) and shred (density equal to 0.949 g/cm3, particle size above 2 mm) (Figure 52). The level of HDPE modification was 5.0 percent by weight of asphalt binder. The asphalt blends were prepared by using a high-shear mixer at 3500 rpm to blend the recycled HDPE (in pellet and shred form) into the asphalt binder at a temperature of 170°C for 60 minutes. For comparison purposes, a conventional styrene-butadiene-styrene (SBS) polymer modified binder (PmB) was also included in the study.

Differential scanning calorimetry (DSC) results indicated 132.7°C as the melting temperature of the pellet form, while the shred form showed 110.7°C and 123.8°C as melting temperatures due to the presence of impurities. Thermogravimetric analysis (TGA) showed that the thermal degradation of the recycled HDPE (in pellet and shred form) occurred around 400°C, indicating that the blending temperature of 170°C would not be detrimental for incorporation of the recycled additive into the asphalt binder. Fourier transform infrared spectrometry (FTIR) results indicated similar peaks for the 70/100 penetration grade binder and the recycled HDPE asphalt blends, showing that the recycled HDPE did not chemically react with the asphalt binder. Environmental scanning electron microscopy (ESEM) images supported the finding that the recycled HDPE interacted with the asphalt binder only by physical process. Viscosity measurements collected with the dynamic shear rheometer (DSR) after the storage stability test (EN-13399) of the recycled HDPE asphalt blends indicated phase separation, with the top portion samples showing higher viscosity values due to the presence of the recycled material in comparison to the bottom portion samples. Ring and ball (R&B) test results showed that the softening point temperature of each recycled HDPE asphalt blend was higher than the 70/100 penetration grade binder and the PmB, indicating that the recycled blends were stiffer. DSR master curves of complex modulus (i.e., stiffness) at high temperatures (i.e, low frequencies) confirmed the higher stiffness of the recycled HDPE asphalt blends in comparison to the 70/100 penetration grade binder and the PmB, which could be a potential advantage for rutting performance. At low temperatures (i.e., high frequencies), the recycled HDPE asphalt blends and

PmB presented similar complex modulus. When comparing between the pellet and shred form of the recycled HDPE, the asphalt blend prepared with the shred form showed higher stiffness than the pellet form, due to its larger particle size. Black diagram results indicate that the recycled HDPE asphalt blends do not behave as a thermo-rheological simple material. Finally, the study provided the following recommendations for future research: incorporation of additives such as waste cooking oil or sulfur to improve the homogeneity and mixability of the recycled HDPE asphalt blends, characterization of the low-temperature properties of recycled HDPE modified asphalt blends, and incorporation of recycled HDPE into the asphalt mixture via the dry process.

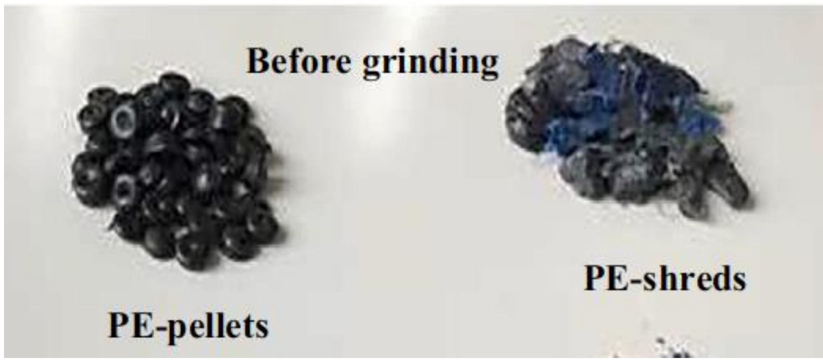


Figure 52. Recycled HDPE in Pellet and Shred Forms

"Use of Road-grade Recycled Plastics for Sustainable Asphalt Pavements: Overview of the Recycled Plastic Industry and Recycled Plastic Types" by F. Giustozzi and Y.J. Boom in an Austroads Report, 2021.

Authors	F. Giustozzi and Y.J. Boom (RMIT University, Australia)
Sponsor	Austroads Ltd
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Technical Guidance

This report provides an overview of the type, volume, and cost of recycled plastics and their potential usages for asphalt paving applications. It introduces post-industrial and post-consumer plastics as the two main streams of recycled plastics. Post-consumer plastics refer to recycled plastics obtained from consumer or commercial markets such as food packaging. Post-industrial plastics refer to recycled plastics obtained from wastes of manufactured and industrial applications. The report discusses the recycling process, mechanical and chemical recycling methods, and challenges associated with these processes. Furthermore, the report provides price ranges for different types of recycled plastics in Australia and New Zealand. As shown in Figure 53, recycled plastics in powder form are generally most expensive, followed by those in pellets/granules, flakes/chips, and bale forms.

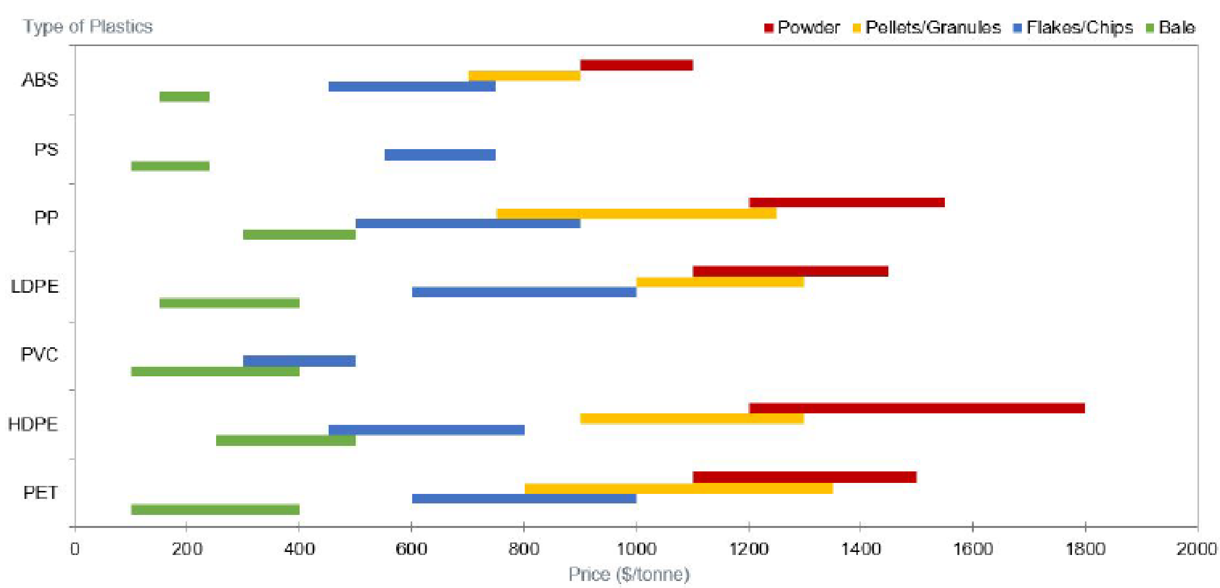


Figure 53. Price Range of Recycled Plastics by Shape in Australia and New Zealand (Giustozzi and Boom, 2021)

The report indicates that polypropylene (PP) and high-density polyethylene (HDPE) plastics are the major sources of post-consumer and post-industrial streams in Australia and New Zealand. Additionally, the report suggests that post-industrial plastics would be more appropriate for general recycling from a commercial point of view. Moreover, the report declares that the full-process recycling of post-consumer plastics is more time-consuming and costly than post-industrial plastics, but certain arrangements could be made to improve the recycling rate for both streams. Additionally, the report suggests excluding certain types of recycled plastics with feasible recyclability in other industries from asphalt pavement applications.

The report suggests that adding recycled plastics via the wet process as binder modifier is economically viable because the cost of standard asphalt polymers is at least double the cost of recycled plastics. Using the dry method in large volumes would be more affordable because of the cost savings associated with the reduced amount of aggregates required for asphalt mixture production. Finally, this report suggests that by using recycled plastics in asphalt pavements, the recycling rate in Australia and New Zealand would improve remarkably, providing significant economic and environmental benefits.

"Feasibility Study on Recycled Vegetable Oil Waste and Recycled Polyethylene for the Modification of Aged Asphalt" by X. Ye, X. Zou, F. Tian, and H. He in *Journal of Plos One*, 2021.

Authors	X. Ye, X. Zou, F. Tian, and H. He (Chongqing Jiaotong University, China)
Sponsor	Unknown
Plastic Type	Low-density Polyethylene (LDPE)
Plastic Addition Method	Wet Process
Plastic Dosage	2 and 4% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing

This study evaluated the impacts of adding recycled low-density polyethylene (LDPE) and waste vegetable oils on the properties of laboratory aged asphalt binders. A 70 penetration-grade asphalt binder was first aged in rotating-film oven (RTFO) and pressurized aging vessel (PAV) and then modified with waste vegetable oils and LDPE for rejuvenation. The vegetable oils were added at four dosages: 5, 10, 15, and 20% by the weight of asphalt binder, while LDPE was added at 2 and 4% by the weight of asphalt binder. A wide variety of laboratory binder tests were conducted to evaluate the physical, rheological, and chemical properties of asphalt binders modified with waste vegetable oils and LDPE.

Test results indicated that adding LDPE decreased the penetration and ductility but increased the softening point of the asphalt binder, but this stiffening effect was counteracted by adding waste vegetable oils. Adding LDPE and a high dosage of waste vegetable oils increased the binder viscosity. The multiple-stress creep recovery (MSCR) test results showed that both waste vegetable oils and LDPE enhanced the rutting resistance and elasticity of the asphalt binder. The dynamic shear rheometer (DSR) $|G^*|\sin(\delta)$ results indicated that adding waste vegetable oils and LDPE improved the fatigue resistance of the asphalt binder; however, the results also showed adverse effects for increasing the LDPE dosage in asphalt binders containing more than 15% waste vegetable oils. The bending beam rheometer (BBR) results showed that waste vegetable oils improved the low-temperature rheological properties of asphalt binders containing LDPE. Among all the binder modification options, adding 15% waste vegetable oils and 4% LDPE yielded the modified aged binders with the best overall rheological properties. Finally, the chemical analysis showed that waste vegetable oils were effective in rejuvenating aged asphalt binders by reducing the amount of carbonyl, sulfoxide, and macromolecules.

"Interim Guidelines for the Use of Recycled Waste Plastic in Local Government Road Surfacing Applications" by A. Remtulla and S. Halligan in *an Austroads Report*, 2021.

Authors	A. Remtulla and S. Halligan (Austroads, Australia)
Sponsor	Unknown
Plastic Type	Not Applicable
Plastic Addition Method	Not Applicable
Plastic Dosage	Not Applicable
Scope	Technical Guidance

This report provides interim guidelines for using recycled plastics in local government road surfacing applications, including asphalt mixture and pavement sealing applications. Specifically, the report discusses different types of recycled plastics available in Australia, what has been used in recent times, how it could be incorporated into asphalt mixture and pavement sealing applications, and flowcharts to assist in procuring products for road surfacing applications. The guidelines offered in this report are applicable to roadways not subjected to a heavy volume of traffic or high proportion of heavy vehicles. Because of the lack of information available, the report offers no or limited guidance on health, safety and environmental matters, costs of commercially available products, procurement of proprietary products, and performance of products currently being use in Australia. These perspectives are being addressed in ongoing research through Austroads, National Asset Centre of Excellence (NACOE) and Western Australian Road Research and Innovation Program (WARRIP) projects.

The report indicates that recycled plastics can be added into the asphalt mixture via the wet process or the dry process to serve as aggregate extender, binder extender, or binder modifier. To ensure the quality of recycled plastics, the report recommends that asphalt contractors establish a quality management system to document: how they will receive the recycled plastics, verify that the supplied materials are the correct type(s) of recycled plastics, stockpile in the correct location, manage stockpiles to ensure traceability of product and avoid product contamination and damage, process the recycled plastics in accordance with a specified process to the requisite size and shape, and store the processed plastic to protect it from rain and contaminants. The report also recommends that asphalt contractors test the processed plastic on a regular basis for melting temperature and melting viscosity as quality check.

The report recommends the use of current binder specifications for assessing the quality of asphalt binders modified with recycled plastics, which include viscosity, torsional recovery, softening point, stress ratio, polymer separation, flash point, and mass loss upon heating requirements. The report suggests the addition of styrene-butadiene-styrene (SBS) polymer or crumb rubber (CR) to help meet the specification requirements of the binder elastic properties. The terminal-blended wet-process plastic modified binders are required to have adequate storage stability to prevent polymer separation during storage and production. When plastic modified binders are produced at the asphalt plant, the binders should be used for mixture production immediately after being produced; otherwise, they should be kept in agitated storage tanks to ensure binder homogeneity.

Regarding asphalt mix design, the report recommends the use of a performance-based mix design approach over the current volumetric mix design approach. The performance-based mix design approach should incorporate traditional volumetric analysis and mixture performance testing to ensure that the plastic modified mixtures have adequate workability, moisture resistance, rutting resistance, fatigue resistance, and stiffness properties. The report provides recommended test criteria for workability and moisture susceptibility evaluations. For rutting resistance and fatigue resistance evaluations, the plastic modified mixtures are required to perform similar to or better than the corresponding conventional asphalt mixtures. The stiffness characterization results are for informational purposes only.

Regarding mixture production, the report indicates that the higher viscosity of plastic modified binders could reduce the overall mixture workability and compactability. Increasing production temperature to overcome this issue, however, is not recommended because it will increase the fume emission and energy consumption associated with plant production. Instead, strategies such as using a softer asphalt binder or using warm mix asphalt additives should be considered but their effectiveness is yet to be determined.

"Recycling of Low-value Packaging Films in Bitumen Blends: A Grey-based Multi Criteria Decision Making Approach considering a Set of Laboratory Performance and Environmental Impact Indicators" by S. Nizamuddin, M. Jamal, J. Santos, and F. Giustozzi in *Journal of Science of the Total Environment,* 2021.

Authors	S. Nizamuddin, M. Jamal (RMIT University, Australia), J. Santos (University of Twente, the Netherlands), and F. Giustozzi (RMIT University, Australia)
Sponsor	Unknown
Plastic Type	Recycled Polyethylene (PE)
Plastic Addition Method	Wet Process
Plastic Dosage	3, 6, 9, and 12% by Weight of Asphalt Binder
Scope	Laboratory Binder Testing, Environmental Impact Assessment

This study evaluated the physio-chemical, rheological, and thermal properties of linear low-density polyethylene (LLDPE)/low-density polyethylene (LDPE) modified binders. Dosages of recycled LLDPE/LLPE pellets (Figure 54), ranging from 3% to 12% (by weight of asphalt binder) were added to a C320 asphalt binder via the wet process. The ring-and-ball softening point, penetration, Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA)/ derivative thermogravimetry (DTG) and modulated differential scanning calorimetry (MDSC) analyses, storage stability, dynamic shear rheometer (DSR) frequency sweep, and multiple stress creep recovery (MSCR) tests were conducted for binder performance characterization. The environmental sustainability was assessed through life cycle assessment (LCA) analysis. The grey relational analysis (GRA) was used to combine laboratory performance evaluation and environmental impact assessment. The multi-attribute decision-making (MADM) method was used to rank the best overall performance.

Laboratory test results indicated that LLDPE/LDPE modification enhanced the physical, rheological, and chemical properties of asphalt binders, where the modified binders had increased softening point, viscosity, penetration index, and rutting resistance but reduced penetration value. The LLDPE/LDPE modified binders also had improved elasticity as indicated by lower phase angle values. Thermal analysis showed increased thermal stability for the asphalt binder after LLDPE/LDPE modification. The LCA results showed a reduced environmental impact associated with the use of LLDPE/LDPE modified binders and mixtures for pavement applications. The performance coefficient results from GRA methodology were analyzed through the MADM method, of which the results indicated that 3% LLDPE/LDPE provided for asphalt binder modification provided the most combined benefits from laboratory performance and environmental impact perspectives.

Figure 54. Recycled LLDPE/LDPE Pellets Processed out of Waste Packaging Films

"Preliminary Evaluation of Plasmix Compound from Plastics Packaging Waste for Reuse in Bituminous Pavements" by C. Celauro, R. Teresi, F. Graziano, F.P. La Mantia, and A. Protopapa in *Journal of Sustainability*, 2021

Authors	C. Celauro (Università degli Studi di Palermo), R. Teresi (Italian National Interuniversity Consortium of Materials Science and Technology), F. Graziano, F.P. La Mantia (Università degli Studi di Palermo), and A. Protopapa (Italian National Consortium for the Collection and Recycling of Plastic packages)
Sponsor	Unknown
Plastic Type	high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET)
Plastic Addition Method	Wet Process, Dry Process
Plastic Dosage	Wet Process: 2% and 5% by Weight of Asphalt Binder Dry Process: 2% by Weight of Aggregate
Scope	Laboratory Binder Testing, Laboratory Mixture Testing

This study evaluated the modification feasibility of Plasmix, a highly heterogeneous mixed plastic derived from post-consumer plastics, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polystyrene (PS), polypropylene (PP), and polyethylene terephthalate (PET). Water floatation was performed on Plasmix, which was then extruded into 2 to 6 mm pellets using a twin-screw extruder (Figure 55). Because of the inhomogeneity of the Plasmix blend, recycled polyethylene (RPE) was added into the mix for extrusion and granulation to improve the homogeneity of the material, which also helped facilitate the dispersion of the plastic materials into the asphalt binder (with 50/70 penetration grade). Both the wet and dry addition methods were used in this study. For the wet process, Plasmix was added at 2% and 5% by weight of asphalt binder. For the dry process, Plasmix was added at 2% by weight of aggregate. Fourier transform infrared spectroscopy- attenuated total reflectance (FTIR–ATR), electron scanning microscope (SEM), and differential scanning calorimetry (DSC) were used for evaluating the chemical structure, morphology properties, and thermal properties of Plasmix, respectively. Penetration, softening point, storage stability (EN 13399), dynamic shear rheometer (DSR), and frequency sweep tests were conducted for Plasmix modified binders prepared via the wet process. For the dry process, the Marshall method was used to prepare asphalt mixtures containing Plasmix. The wheel tracking test was conducted to evaluate the permanent deformation of asphalt mixtures with and without Plasmix modification. The conventional binder test results showed decrease in penetration and increase in stiffness and viscosity of the asphalt binder after adding Plasmix. The modified binders showed more elastic behavior than the unmodified binder in DSR testing. The wheel tracking test results indicated that adding Plasmix improved the high-temperature permanent deformation of the asphalt mixture. Overall, the test results demonstrated the performance benefits of adding Plasmix for asphalt binder and mixture modifications.

Figure 55. Plasmix Before (Left) and After (Right) Extrusion and Granulation (Celauro et al., 2021)