Preliminary Investigation (PI-0282)

Caltrans Division of Research, Innovation and System Information

Use of Recycled Plastic in Asphalt and Concrete Pavement Applications

Requested by
Tom Pyle, Office of Asphalt Pavements

December 3, 2020

The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation, the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.

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Executive Summary

Background

Waste plastics such as plastic drink bottles and single-use plastic bags can have a significant impact on terrestrial and marine ecosystems. Recycling is an obvious environmentally friendly approach to mitigate the environmental impact as it provides opportunities to reduce oil usage, carbon dioxide emissions and the quantities of waste requiring disposal. Consequently, there is global interest in recycling and reuse of waste plastics, and significant progress has been made toward the incorporation of waste plastics into asphalt and concrete pavement applications.

Many stakeholders, including the California State Legislature, have expressed interest in how recycled plastics can be used in pavement materials in the construction, maintenance or rehabilitation of a highway or road. For example, Senate Bill 1238 would have authorized a study to assess the feasibility, cost-effectiveness and environmental benefits of including recycled plastics in pavement and would have required Caltrans to update its specifications, if appropriate. California Department of Transportation (Caltrans) expects interest in these processes to continue and is therefore seeking information about the use of commercially available recycled plastic products in asphalt and concrete pavement applications. These materials might include aggregate bases and subbases, binders, materials for pothole repair, and other novel uses of recycled plastic to produce asphalt and concrete materials. Of particular interest are the latest industry practices and international experiences, especially with regard to the recycled plastics most widely used.

To assist with this information-gathering effort, CTC & Associates conducted a literature search of domestic and international in-progress and published research and consulted with selected experts in this field of study.

Summary of Findings

Research and Related Resources

The literature search of recent publicly available domestic and international resources gathered information and identified a representative sampling of publications that are organized into the following topic areas:

- Background.
- Recycled plastics used in pavement applications.
- Commercial suppliers.

Background

Resin Identification Codes

Typically, researchers and commercial suppliers examining the use of commercially available recycled plastic products in asphalt and concrete pavement applications indicate the type of plastic used in the application using the polymer name, a resin identification code (RIC), or both.

The California Department of Resources Recycling and Recovery (CalRecycle) web site provides a summary of the types of plastics that can be recycled. Table ES1 identifies the RICs

(*Recycling No*. in the table) and the associated polymer names and abbreviations that appear throughout this Preliminary Investigation.

Table ES1. Plastic Recycling Numbers/Resin Identification Codes

Recycling No.	Symbol	Abbreviation	Polymer Name	Uses Once Recycled
1	1 PETE	PETE or PET	Polyethylene terephthalate	Polyester fibers, thermoformed sheet, strapping and soft drink bottles.
2	2 HDPE	HDPE	High-density polyethylene	Bottles, grocery bags, recycling bins, agricultural pipe, base cups, car stops, playground equipment and plastic lumber.
3	3 V	PVC or V	Polyvinyl chloride	Pipe, fencing and nonfood bottles.
4	4 LDPE	LDPE	Low-density polyethylene	Plastic bags, six-pack rings, various containers, dispensing bottles, wash bottles, tubing and various molded laboratory equipment.
5	5 PP	PP	Polypropylene	Auto parts, industrial fibers, food containers and dishware.
6	6 PS	PS	Polystyrene	Desk accessories, cafeteria trays, toys, videocassettes and cases, and insulation board and other expanded polystyrene products (e.g., Styrofoam).
7	7 OTHER	Other	Other plastics, including acrylic, acrylonitrile butadiene styrene, fiberglass, nylon, polycarbonate and polylactic acid.	

Source: *Just the Facts*, CalRecycle, January 2020; https://www.calrecycle.ca.gov/bevcontainer/consumers/facts.

Processing Methods

The National Center for Asphalt Technology (NCAT), a partnership between Auburn University and the National Asphalt Pavement Association Research and Education Foundation, describes two methods commonly used to incorporate recycled plastics into asphalt mixtures:

- *Dry process*. Recycled plastics are ground up into smaller sizes and added directly to the mixture either as a partial aggregate replacement or a mixture modifier.
- *Wet process*. Recycled plastics are added to the asphalt binder as with polymer modifiers, where mechanical mixing is required to achieve a homogenous plastics-modified binder blend.

A fall 2019 NCAT news release noted that both processes “have implementation challenges. For the dry process, there is a concern about the lack of consistency in the quality of the final produced mixtures. For the wet process, a major limitation is poor storage stability of the plastic-modified binder, where the plastic tends to separate from the asphalt binder due to the difference in density and viscosity as well as the chemical incompatibility between the two components."

California Experience

Two pilot paving projects completed in California have used recycled plastics. A Caltrans District 3 project used a mixture of pavement grindings with a liquid plastic polymer binder to repave a section of Highway 162. A University of California San Diego project used asphalt containing recycled plastic materials instead of petroleum-based bitumen as a binder on a campus roadway that will be tested for wear and other factors to determine its viability for usage beyond this test site.

Waste Characterization Studies

CalRecycle prepares periodic waste characterization studies that provide data to help public agencies plan how to reduce waste, set up recycling programs, and conserve money and resources. The May 2020 report, *2018 Facility-Based Characterization of Solid Waste in California*, "estimates the quantity and composition of the commercial, residential and self-hauled waste streams in California and aggregates this data to estimate the overall composition." The waste stream examined in the May 2020 report includes the types of plastics considered for use in asphalt and concrete pavement applications.

<u>Recycled Plastics Used in Pavement Applications</u>

The research and related resources in this section of the report are organized by the type of recycled plastic referenced in the publication. The tables beginning on page 7 summarize the publications and other resources highlighted in this Preliminary Investigation in these topic areas:

- Unspecified or multiple RICs.
- RIC 1, polyethylene terephthalate.
- RIC 2, high-density polyethylene, and/or RIC 4, low-density polyethylene.
- RIC 2, high-density polyethylene; RIC 4, low-density polyethylene; and RIC 5, polypropylene.
- RIC 6, polystyrene.

<u>Commercial Suppliers</u>

Four commercial suppliers of materials that employ recycled plastics in pavement are highlighted with excerpts from web sites, descriptions of pilot projects and relevant research. These companies include:

- *Dow* (Midland, Michigan). Dow has completed two small projects on private roads in Texas and a recycled plastics application on a public road in Michigan. The Texas projects used asphalt binders modified with recycled plastics that employed a wet process that used binder modified with 1.5% linear low-density polyethylene post-consumer plastics, Elvaloy copolymer, and polyphosphoric acid.
- *MacRebur Ltd.* (Lockerbie, United Kingdom). MacRebur provided the paving material used for a University of California San Diego test site. The company uses a dry-mixing process to produce three products that use shredded and pelletized recycled waste plastics to replace a percentage of the binder volume. Binder replacement for these products is in the range of 6% to 10%, with 6% recommended as optimal.

- *PlasticRoad* (Vianen, Netherlands). The PlasticRoad consortium produces a prefabricated, modular and hollow road structure based on recycled plastics.
- *TechniSoil Industrial LLC* (Redding, California). TechniSoil technology was used in a Caltrans District 3 pilot project on Highway 162. The company's web site describes its process as a modification of cold-in-place recycling, with a recycling "train" of equipment milling the existing roadway to crush and size the recycled asphalt pavement (RAP). The RAP is then mixed with TechniSoil's G5 liquid plastic polymer binder, which is made in part of discarded plastic bottles, and the recycled mixture is immediately paved back onto the roadway.

Consultation With Selected Experts

To supplement literature search findings, CTC contacted subject matter experts on the use of recycled plastic in asphalt and concrete applications.

State Agencies

CTC convened a discussion with CalRecycle staff members about the use of recycled plastics in asphalt and concrete pavements. In addition to CalRecycle's expertise in the use of recycled plastics, the agency has a significant level of experience evaluating the use of waste tires in pavement applications and has found that crumb rubber from recycled tires provides better performance. Staff members voiced concern that a movement away from the current diversion of scrap rubber for use in pavement applications to use of plastics classified as RIC 1 or RIC 2, which are easily recycled using other means, will upset current plastics recycling streams.

The CalRecycle team also noted that there is little domestic research on the use of waste plastics in asphalt, and commercial supplier claims of strength and other benefits of the use of plastic in paving materials require further review. Other issues for further review, particularly domestically, include the environmental impacts associated with the potential for plastic used in asphalt to move from the roadway into the environment. There are also other environmental issues, such as whether asphalt made with plastic can be safely recycled after reaching its useful life.

Academic Institutions

CTC contacted DingXin Cheng, director of the California Pavement Preservation Center at California State University, Chico, to discuss his experience with the use of recycled plastics in pavement applications. Cheng noted that domestic research in this area is limited, and both field and laboratory research would be beneficial. (California Pavement Preservation Center expects to conduct research in this area in 2021/2022.) Topic areas recommended for future research:

- The effectiveness of the dry versus wet processing method.
- The impact of plastic on pavement performance and how its performance compares to rubberized asphalt.
- The viability of using recycled plastics to introduce plasticity in order to make pavement more movable and improve mechanical performance.
- The effectiveness and environmental impact of recycling pavements incorporating plastics at an early age (after seven to 10 years of use).
- Other environmental considerations, such as the best blending temperature to limit emissions.

Gaps in Findings

As the experts contacted for this Preliminary Investigation noted, and as the sampling of citations included in this report indicate, little domestic research has been conducted on this topic. While international research is more extensive, it is not clear how these research results will transfer to the domestic use of recycled plastics in pavement. Neither domestic nor international research has appeared to address the environmental impacts of production, installation and possible recycling of pavements made with recycled plastics.

The number of known pilot sites in the United States that have used recycled plastics in the paving mix is limited and represents relatively recent installations. (The pilot sites highlighted in this Preliminary Investigation were installed in the last two years.) More time is needed to determine the performance and impacts of these pavements in the field. Finally, state and national research expected to begin in 2021 or soon after may yield results of interest to the State of California.

Next Steps

Moving forward, Caltrans could consider:

- Reviewing some of the more recent international research cited in this report to assess its relevance to California's interest in the use of recycled plastics in pavements.
- Examining in more detail the pilot sites that used recycled plastics in the pavement:
    - Dow's pilot sites in Texas and Michigan.
    - University of California San Diego's pilot site completed using materials provided by MacRebur Ltd.
    - Caltrans District 3 Highway 162 pilot site completed in collaboration with TechniSoil Industrial LLC.
- Conferring with the researchers conducting Texas Department of Transportation's (DOT's) two-year feasibility study on building roads using recycled plastic mixed with asphalt to learn more about the project.
- Monitoring the progress of National Cooperative Highway Research Program (NCHRP) Project 09-66: Mechanical Properties of Laboratory Produced Recycled Plastic Modified Asphalt Binders and Mixtures, which is expected to begin March 2021. This research will examine the performance properties of asphalt mixtures when recycled plastic waste is added using a plant-mixed or dry process.
- Tracking the progress of a Federal Highway Administration-sponsored Exploratory Advanced Research project that will apply the wet process. NCHRP expects to coordinate NCHRP Project 09-66 with the Exploratory Advanced Research project.
- Continuing to monitor developments in this topic area to identify new pilot sites and newly published findings from domestic and international research.

Unspecified or Multiple RICs

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
NCHRP Project 09-66: Performance Properties of Laboratory Produced Recycled Plastic Modified (RPM) Asphalt Binders and Mixtures (Pending Research)	Domestic National	Seeks to evaluate the impact of post-consumer recycled plastic waste, including but not limited to LDPE, HDPE and polypropylene, on the performance properties of asphalt mixtures when added using a plant-mixed or dry process. NCHRP expects to coordinate this project with the Federal Highway Administration-sponsored research cited below that will apply the wet process. The NCHRP research is expected to begin March 2021.
Topic 3: Compatibilization of Waste Plastic to Enhance Mechanical Properties of Asphalt Cement (Anticipated Research)	Domestic National	Seeks to explore compatibilization—the addition of a third material to two immiscible materials or modification of one or both materials to provide for compatibility—as it relates to the use of post-consumer waste plastic in highway construction.
Building Roads From Plastic Recyclables: With TxDOT Grant, UTA Team to Test Feasibility of Recycled Plastics in Road Construction (2020)	Domestic Texas	Describes a Texas DOT-funded two-year feasibility study on building roads using recycled plastic mixed with asphalt "for an ideal consistency to keep the road safe for motorists and help it last longer, cost less and avoid cracking."
A Synthesis on the Effects of Two Commercial Recycled Plastics on the Properties of Bitumen and Asphalt (2020)	International Australia	Examines various research efforts to understand the effects of two commercially available recycled plastics, known as MR6 and MR10, on bituminous binders and asphalt mixtures. Results indicate that the effects of MR6 and MR10 were generally similar to the effects associated with conventional polymer modification of asphalt binders and asphalt mixtures, particularly those effects associated with plastomeric polymers.
Viability of Using Recycled Plastics in Asphalt and Sprayed Sealing Applications (2019)	International Australia	Examines the viability of using recycled plastics in asphalt and sprayed seals by Australian and New Zealand road authorities. Findings indicate that waste plastic can act as a partial aggregate replacement in bituminous mixes and a binder extender without having any significant influence on the properties of the asphalt mix.
Strength Evaluation of Utilizing Recycled Plastic Waste and Recycled Crushed Glass in Concrete Footpaths (2019)	International Australia	Describes the incorporation of recycled plastic waste (RPW) and recycled crushed glass (RCG) as coarse aggregate replacement in concrete mixture and to evaluate its feasibility for concrete footpath construction. Coarse aggregate replacement was found to be viable up to 20% by volume for RPW and up to 30% by volume for RCG for use in footpath construction.
Laboratory Evaluation of Asphalt Containing Recycled Plastic as a Bitumen Extender and Modifier (2019)	International Australia	Evaluates two commercially available recycled waste plastic products in the laboratory: one product is intended to be plastomeric, the other elastomeric. Further research is recommended to better understand the modest reduction in moisture damage resistance associated with recycled plastic, as well as the digestion of recycled plastic using the dry-mixing process.

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Waste Plastic as Additive in Asphalt Pavement Reinforcement: A Review (2019)	International Australia	Describes findings that indicate using waste plastic as an additive in asphalt reinforcement has shown significant improvement on its engineering properties, which enhances the modified asphalt resistance to rutting, fatigue, deformation and moisture stability. Researchers noted that previous studies recommended 4% of waste HDPE "as [the] best content to achieve better asphalt performance properties in term[s] of stiffness and rutting resistance," but that other studies recommended "waste PET up to 6[%]-8% as an ideal modifier."
Recycled Waste Plastic for Extending and Modifying Asphalt Binders (2018)	International Australia	Assesses the use of three commercially available recycled plastic products for bituminous binder extension and modification in asphalt mixtures. Using a dry-mixing process, shredded and pelletized recycled waste plastics replaced 6% of the binder volume.
Laboratory Evaluation of the Effect of Composite Modifier on the Performance of Asphalt Concrete Mixture (2017)	International China	Describes development of a composite modifier (CM) of asphalt concrete (AC) mixture containing crumb tire rubber, recycled plastic particles and styrene-butadiene-styrene (SBS) to evaluate the effect of the modifier on performance of the AC mixture. Results show the addition of CM in AC mixtures can significantly improve high-temperature performance compared to the control mixture, but the unsuitable dosage of CM may have some adverse effect on low-temperature performance and moisture susceptibility.
Impact Performance of Recycled Plastic-Based Concrete (2015)	International China	Reports on an experimental study on recycled plastic concrete (RPC) that uses acrylonitrile-butadiene-styrene/polycarbonate copolymer (ABS/PC) plastic particles to replace 5%, 10%, 15% and 20% (in volume) of fine aggregate sand. Results showed that the energy absorption capability of RPC was higher than that of normal concrete (NC) and increased with the plastic content. The impact resistance performance of RPC materials was superior to that of NC.
Performance of Stone Matrix Asphalt and Asphaltic Concrete Using Modifiers (2018)	International India	Proposes the use of fiber extracted from waste plastic in bituminous mixes for road construction. Researchers studied the modification of AC with processed waste plastic in granular form using varying lengths of fibers (2, 4, 6 and 8 mm), which were added to the AC mixtures. AC mixtures with 0%, 4%, 6%, 8%, 10% and 12% waste plastic by weight of bitumen were prepared. Researchers noted the "effect of the preceding on drain down, Marshall stability and indirect tensile strength was promising."
Utilization of Waste Polymers for Flexible Pavement and Easy Disposal of Waste Polymers (2010)	International India	Describes a technique that coats heated stone aggregate with plastics generated from recycled plastic wastes. The coated aggregate is then mixed with 60/70 or 80/100 bitumen, and the mix is used for road construction.

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Optimum Use of Plastic Waste to Enhance the Marshall Properties and Moisture Resistance of Hot Mix Asphalt (2014)	International Iraq	Focuses on the Marshall test and index of retained strength to determine the properties of plastic waste particles such as size, thickness and percent of content that provide the ultimate performance of hot mix asphalt. Findings indicate that added plastic waste with fine particle size (passing sieve No.16 (1.18 mm), thin thickness (0.2 mm) and 5% by weight of aggregate) increase the Marshall stability and the index of retained strength by 20% and 15%, respectively, more than the conventional mix.
Asphalt Surface Mixtures With Improved Performance Using Waste Polymers via Dry and Wet Processes (2017)	International Italy	Evaluates the mechanical performance of a typical surface course mixture modified with two different plastic wastes using wet and dry processes. Results indicate that the polymer-modified mixtures showed similar or improved performance when compared with that of a conventional control mixture produced with a harder virgin grade bitumen.
Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification (2019)	International Saudi Arabia	Examines a combined form of RPW used as a mineral aggregate supplement in a dense-graded hot mix asphalt AC made with RPW-modified asphalt binder. Results showed that combined RPW as an aggregate supplement has advantages over the use of recycled PET-only aggregates. The hybrid RPW-AC showed superior performance compared to the reference mixtures.

RIC 1, Polyethylene Terephthalate

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Performance Properties of Polyethylene Terephthalate Particle-Based Concrete: A Review (2017)	Domestic	Describes prior research results on mechanical properties of PET concrete that demonstrate the strength of concrete decreases with increasing the PET replacement ratio. The toughness of PET concrete is higher than the normal concrete, which may permit its use in pavement engineering applications where impact and dynamic loads govern the design.
Effects of Waste Polyethylene on the Rheological Properties of Asphalt Binder (2020)	International China	Examines three types of PE used to prepare modified binders with contents ranging from 2% to 6%. Among the findings: • The high-temperature properties of asphalt binders could be effectively improved by the PE modifiers with different types and contents. • Fatigue properties of PE-modified binders were improved, especially at the lower shear strain range. • The PE modifier had a negative effect for asphalt binder on the low-temperature property.

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Recycling of Polyethylene Terephthalate (PET) Plastic Bottle Wastes in Bituminous Asphaltic Concrete (2016)	International Nigeria	Evaluates the effects of recycling PET plastic bottle wastes in bituminous asphaltic concrete (BAC) used in flexible pavement construction. Polymer-coated aggregate (PCA)-modified BAC seems preferable because it has the potential to use more plastic wastes with a higher optimum plastic content of 16.7% by weight of total aggregates and filler compared to that of 9% by weight of optimum bitumen content achieved by polymer-modified bitumen-BAC.
An Approach to the Usage of Polyethylene Terephthalate (PET) Waste as Roadway Pavement Material (2014)	International Turkey	Investigates the use of two novel additive materials—thin liquid polyol PET (TLPP) and viscous polyol PET (VPP), which were chemically derived from waste PET bottles and used to modify the base asphalt separately. Researchers used conventional tests (penetration, softening point, ductility, Marshall stability and Nicholson stripping) and Superpave methods (rotational viscosity, dynamic shear rheometer and bending beam rheometer) to assess performance.

RIC 2, High-Density Polyethylene, and/or RIC 4, Low-Density Polyethylene

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Stiffness Properties of Recycled Concrete Aggregate With Polyethylene Plastic Granules in Unbound Pavement Applications (2016)	International Australia	Evaluates two types of recycled waste materials—recycled concrete aggregate (RCA) and HDPE and LDPE—for their stiffness and resilient characteristics. Because the polyethylene plastics in this research were used in the form of granules instead of reinforcing fibers, a slight degradation of RCA properties was observed.
Pavement Properties of Asphalt Modified With Packaging-Waste Polyethylene (2014)	International China	Examines recycled packaging waste polyethylene (WPE) to replace ordinary polymer modifier in the modification of raw asphalt. The high-temperature stability, anti-cracking properties at low temperature, life span and stability against water of the asphalt mixture were improved, a finding which is attributed to the properties and characteristics of WPE, the swelling of sheared WPE and the WPE/asphalt network structure.
Plastic Roads: Use of Waste Plastic in Road Construction (2017)	International India	Reviews use of shredded plastic waste to act as a strong "binding agent" for tar. Findings indicate that "tests at the laboratory level proved that the bituminous concrete mixes prepared using the treated bitumen binder fulfilled all the specified Marshall mix design criteria for surface course of road pavement. … Another important observation was that the bituminous mixes prepared using the treated binder could withstand adverse soaking conditions under water for longer duration."

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Plastic Roads: A Recent Advancement in Waste Management (2016)	International India	Presents a summary of "[c]onsiderable research [that] has been carried out to determine the suitability of plastic wastes in the construction of bituminous pavements." The authors note that "[s]tudies have showed that the use of recycled polyethylene in bituminous pavement mixes reduces the permanent deformation in the form of rutting and the low temperature cracking of pavement surfacing."
Effect of Waste Plastics Utilization on Indirect Tensile Strength Properties of Semi Dense Bituminous Concrete Mixes (2014)	International India	Describes the use of plastic in bituminous concrete to get improved properties. Researchers conducted Marshall tests, indirect tensile strength tests and degradation tests with trial waste plastic content added along with aggregates to find the influence of plastic addition to semi-dense bituminous concrete mix.
Incorporation of Waste Plastic in Asphalt Binders to Improve Their Performance in the Pavement (2013)	International Portugal	Examines the suitability of granulated and powder polymers in bitumen modification to assess the potential [for] using recycled polymers in asphalt mixtures. The studied polymers were ethylene-vinyl acetate (virgin and recycled), SBS (virgin), HDPE (recycled), LDPE (recycled), acrylonitrile-butadiene-styrene (recycled) and crumb rubber from used tires (recycled). The characterization of the different bitumens modified with 5% of each of the studied polymers demonstrated that it is possible to obtain similar properties, or even better, than those of a commercial modified bitumen.
Use of Plastic Wastes From Greenhouse in Asphalt Mixes Manufactured by Dry Process (2019)	International Spain	Assesses the applicability of LDPE, recycled from greenhouses used in agriculture, as a modifier of asphalt mixes manufactured by a dry process. Compared to a mix manufactured with a polymer-modified bitumen 45/80-65, plastic addition led to a poorer mix performance in terms of particle loss and fatigue resistance.
Modification of a 14mm Asphalt Concrete Surfacing Using RAP and Waste HDPE Plastic (2010)	International United Kingdom	Reports the findings of a laboratory investigation to assess the use of waste HDPE plastic and RAP to improve the performance of a 14 mm AC surfacing. Deformation and fatigue testing of a 14 mm asphalt concrete mix surfacing mix incorporating a blend of waste HDPE plastic and RAP carried out at a range of test temperatures found that modification using waste HDPE plastic and RAP improved both deformation and fatigue properties.

RIC 2, High-Density Polyethylene; RIC 4, Low-Density Polyethylene; and RIC 5, Polypropylene

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
A Study on the Plastic Waste Treatment Methods for Road Construction (2017)	International India	Reviews experiments that indicated that waste plastic, when added to hot aggregate, will form a fine coat of plastic over the aggregate, and the aggregate, when mixed with the binder, is found to give higher strength, higher resistance to water and better performance over a period of time.
Performance of Recycled Plastic Waste Modified Asphalt Binder in Saudi Arabia (2017)	International Saudi Arabia	Concludes that the upper performance grade limit increases by almost one level for every 2% increase in the LDPE or HDPE content. The improvement of the rutting performance indicator is more significant in the HDPE samples than in the LDPE and PP blends.

RIC 6, Polystyrene

Publication or Project (Year)	Domestic or International	Excerpt From Abstract or Description of Resource
Development of Ecofriendly Concrete Incorporating Recycled High-Impact Polystyrene From Hazardous Electronic Waste (2015)	International India	Explores the use of recycled computer plastic waste made into chips. Coarse aggregate was partially replaced with high-impact polystyrene (HIPS) by volume percentages of 10%, 20%, 30%, 40% and 50% for different water-cement ratios such as 0.53, 0.49 and 0.45. Various volume percentages of HIPS aggregate replacement show a linear relation between the loss of strength and increase in HIPS content. Researchers noted that this type of concrete can be used in nonstructural elements such as partition walls and lightweight roofs.

Detailed Findings

Background

Waste plastics such as plastic drink bottles and single-use plastic bags can have a significant impact on terrestrial and marine ecosystems. Recycling is an obvious environmentally friendly approach to mitigate the environmental impact as it provides opportunities to reduce oil usage, carbon dioxide emissions and the quantities of waste requiring disposal. Consequently, there is global interest in recycling and reuse of waste plastics, and significant progress has been made toward the incorporation of waste plastics into asphalt and concrete pavement applications.

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Research and Related Resources

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- Commercial suppliers.

Background

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Typically, researchers and commercial suppliers examining the use of commercially available recycled plastic products in asphalt and concrete pavement applications indicate the type of plastic used in the application using the polymer name, an RIC or both.

RICs were developed in the 1980s to allow for consistency in plastics manufacturing and the processing of recycled plastics. An ASTM International standard—ASTM D7611, Standard Practice for Coding Plastic Manufactured Articles for Resin Identification—“guides stakeholders in properly identifying manufactured articles made from various resin materials, ultimately helping to facilitate the desired recycling of these products.” (See Supporting Document below for more information about RICs.)

The California Department of Resources Recycling and Recovery (CalRecycle) web site provides a summary of the types of plastics that can be recycled. Table 1 identifies the RICs (*Recycling No*. in the table) and the associated polymer names and abbreviations that appear throughout this Preliminary Investigation.

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5	5 PP	PP	Polypropylene	Auto parts, industrial fibers, food containers and dishware.
6	6 PS	PS	Polystyrene	Desk accessories, cafeteria trays, toys, videocassettes and cases, and insulation board and other expanded polystyrene products (e.g., Styrofoam).
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Supporting Document

ASTM D7611, Standard Practice for Coding Plastic Manufactured Articles for Resin Identification: Guiding the Plastics Recycling Value Chain, ASTM International, undated.
https://www.astm.org/COMMIT/d7611.pdf
This brochure provides codes for the six most commonly found resin types, with a seventh category created for all other types.

Processing Methods

The National Center for Asphalt Technology (NCAT), a partnership between Auburn University and the National Asphalt Pavement Association Research and Education Foundation, describes two methods commonly used to incorporate recycled plastics into asphalt mixtures:

- *Dry process*. Recycled plastics are ground up into smaller sizes and added directly to the mixture either as a partial aggregate replacement or a mixture modifier.
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A fall 2019 NCAT news release (see Supporting Documents below) noted that both processes "have implementation challenges. For the dry process, there is a concern about the lack of consistency in the quality of the final produced mixtures. For the wet process, a major limitation is poor storage stability of the plastic-modified binder, where the plastic tends to separate from the asphalt binder due to the difference in density and viscosity as well as the chemical incompatibility between the two components."

The news release noted that NCAT researchers were working on a study sponsored by the Plastics Industry Association "involving chemical characterization and performance testing of asphalt binders and mixtures modified with recycled polyethylene [RPE] materials." Study findings published March 2020 (see Supporting Documents below) included the following recommendations for future research:

- Mechanistic-empirical pavement design analyses to determine the impact of RPE-modified mixtures on the structural response and capacity of asphalt pavements under traffic.
- Research on life cycle cost analysis, life cycle assessment and recyclability evaluation to ensure that adding RPE has no negative impact on the cost-effectiveness, environmental impact and recyclability of asphalt pavements, or any unintended consequences on the health and safety of plant operators and construction crews.
- Low-risk demonstration projects to identify the potential changes in the production and construction practices of RPE-modified asphalt mixtures.

Supporting Documents

Performance Evaluation and Chemical Characterization of Asphalt Binders and Mixtures Containing Recycled Polyethylene, Plastics Industry Association, March 2020.
https://www.plasticsindustry.org/sites/default/files/PLASTICS%20NEMO%20Film%20Phase%20III%20Final%20Report%2003102020.pdf
The two objectives of this study were to "characterize the chemical and rheological properties of asphalt binders modified with RPE and reactive elastomeric terpolymers (RET) as compatibilizers and performance-enhancing additives" and "determine the impact of using both

RPE and RPE plus RET for asphalt modification on the rutting, cracking and moisture resistance of asphalt mixtures."

The report's conclusions, which begin on page 40, provide a summary of the study's laboratory experiments:

> This study sought to determine the feasibility of using RPE alone and RPE plus RET for asphalt modification and evaluate their impacts on the performance properties of asphalt binders and mixtures. To accomplish the research objectives, three laboratory experiments were conducted; the first experiment focused on storage stability, florescent microscopy and rheology testing of RPE and RPE+RET modified binders. In the second experiment, analytical chemical analyses were conducted to determine the infrared spectroscopy, thermal properties, component fractions and molecular weight distribution of selected RET and RET+RET modified binders in comparison to the neat and SBS [styrene-butadiene-styrene] modified binders. Finally, the last experiment focused on mixture performance testing to assess the impact of using RPE and RPE+RET for asphalt modification on the rutting, cracking and moisture resistance of asphalt mixtures.

Related Resource:

> **"Research Needed on Using Recycled Plastics in Asphalt,"** National Center for Asphalt Technology, *Asphalt Technology News*, Vol. 31, No. 2, Fall 2019.
> http://www.eng.auburn.edu/research/centers/ncat/newsroom/2019-fall/plastics.html
> Page 7 of this newsletter provides background information on the use of recycled plastics in asphalt pavement, highlights previous research and pilot efforts, and describes the research in progress associated with the study cited above.

California Experience

Two pilot paving projects completed in California using recycled plastics are described in the Supporting Documents cited below. A Caltrans District 3 project that repaved a section of Highway 162 used a mixture of pavement grindings with a liquid plastic polymer binder. A University of California San Diego project used asphalt containing recycled plastic materials instead of petroleum-based bitumen as a binder.

Supporting Documents

"Caltrans Repaves Roadway With Recycled Plastic Bottles," News Release, California Department of Transportation, July 2020.
https://dot.ca.gov/news-releases/news-release-2020-024
From the news release: Caltrans will repave a section of Highway 162 in Oroville this week using recycled asphalt pavement and liquid plastic made with single-use, plastic bottles—the first time the department has paved a road using 100[%] recycled materials. The pilot project features work on three lanes of a 1,000-foot highway segment. The department is testing the material for later use throughout the state. A one-mile segment of pavement using this treatment will recycle 150,000 plastic bottles.

….

The "plastic" roadway has been found in previous tests to be more durable and last two to three times longer than traditional hot-mixed asphalt pavement. This pilot will be the first test on a state highway.

….

Using this new technology developed by TechniSoil Industrial of Redding, a recycling train of equipment grinds up the top 3 inches of pavement and then mixes the grindings with a liquid plastic polymer binder, which comes from a high amount of recycled, single-use bottles. The new asphalt material is then placed on the top surface of the roadway, eliminating the need for trucks to bring in outside material for a paving operation. By eliminating the need to haul asphalt from the outside, this process can significantly cut greenhouse gas emissions.

"On the Road to Solving Our Plastic Problem," Jade Grifin, *News*, University of California San Diego, October 2018.
https://www.universityofcalifornia.edu/news/road-solving-our-plastic-problem
From the news post: The campus enlisted the UK-based company MacRebur Ltd.[,] to test out its patented plastic roads concept on a portion of Miramar Street at Regents Road, near the Mesa Nueva Graduate Student Housing. The asphalt contains recycled plastic materials instead of petroleum-based bitumen as a binder.

MacRebur created the "plastic road" technology to address two key global issues: what to do with all the plastics on the planet, and maintaining roads around the globe in a cleaner way. UC [University of California] San Diego Construction Commodity Manager Gary Oshima first came upon the novel technology in a Facebook post, featuring a TED [T]alk by MacRebur co-founder and CEO Toby McCartney.

He contacted the company, which expressed interest in finding a location to introduce their product in the U.S. MacRebur had already installed their roadways in the U.K. and Australia, with favorable results. The company offered to donate the plastic for the first installation on campus, and a partnership was conceived.

….

The campus will test the new asphalt road for wear and other factors to determine its viability for usage beyond UC San Diego.

Waste Characterization Studies

CalRecycle prepares periodic waste characterization studies that provide data to help public agencies plan how to reduce waste, set up recycling programs, and conserve money and resources. The May 2020 report cited below, *2018 Facility-Based Characterization of Solid Waste in California*, "estimates the quantity and composition of the commercial, residential and self-hauled waste streams in California and aggregates this data to estimate the overall composition." The waste stream examined in this report includes the types of plastics considered for use in asphalt and concrete pavement applications. A study in progress will update the 2020 report.

Supporting Document

2018 Facility-Based Characterization of Solid Waste in California, California Department of Resources Recycling and Recovery, May 2020.
https://www2.calrecycle.ca.gov/Publications/Download/1458
From the executive summary:

> In 2018, the California Department of Resources Recycling and Recovery (CalRecycle) completed the fifth statewide waste characterization study. CalRecycle contracted with Cascadia Consulting Group to characterize and quantify the disposed waste stream into 94 material types for the commercial, residential and self-haul sectors in California.
>
> ….

In addition, this study also characterized processing residuals from materials recovery facilities (MRFs) to estimate the quantity and composition of residuals generated from four types of MRFs in two regions of the state. CalRecycle's most recent MRF residual study was completed in 2006, and this 2018 data gives an updated picture of residuals disposed from the recycling stream. The information can be used to evaluate potential policy and technology changes that may improve processing with the goal to further increase diversion.

Recycled Plastics Used in Pavement Applications

Unspecified or Multiple RICs

Domestic Resources

National

Pending Research: NCHRP Project 09-66: Performance Properties of Laboratory Produced Recycled Plastic Modified (RPM) Asphalt Binders and Mixtures, request for proposals close date: November 2020; anticipated start date: March 2021.
Project description at https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4961
From the project description:

> **Background**
> ….
>
> There is a mounting body of literature on the use of recycled plastic waste in asphalt, but much of this work lacks a clear experimental plan and suffers from the use of dated test methods. This project will assess the feasibility of using RPM asphalt mixtures as a sustainable solution for both improving the performance of asphalt pavements and reducing the amount of plastic waste in the United States. FHWA [Federal Highway Administration] is funding research to evaluate the compatibility and stability of post-consumer recycled (PCR) plastics with asphalt binder prepared by the wet process [see Topic 3 at https://beta.sam.gov/opp/388c42b92596448e9961274d5e58b640/view]. The project will work concurrently with the FHWA project to evaluate RPM asphalt mixtures produced by the plant-mixed or dry process.
>
> **Objective**
> The objective of this research is to evaluate the impact of post-consumer recycled plastic waste, including, but not limited to, low density polyethylene (LDPE), high density polyethylene (HDPE) and polypropylene (PP), on the performance properties of asphalt mixtures when added using a plant-mixed or dry process.
>
> *Note: NCHRP expects coordination of this project with the FHWA-sponsored research on the compatibility of asphalt binders with recycled plastics.* [See the citation below.]

Anticipated Research: Topic 3: Compatibilization of Waste Plastic to Enhance Mechanical Properties of Asphalt Cement, FHWA 2020 Exploratory Advanced Research Broad Agency Announcement 693JJ3-20-BAA-0001, Exploratory Advanced Research, Federal Highway Administration, contract opportunity original published date: February 3, 2020.
Announcement available at https://beta.sam.gov/opp/75f5fea0e3ec47d08bc2ffb9d7b34c33/view
From the announcement: The most common type of plastics in the municipal waste stream include polyethylene terephthalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE) and polyvinyl chloride (PVC). Given the ubiquity of asphalt pavements

nationwide, there exists an opportunity for significant reductions in landfilled plastics by incorporating these materials into asphalt mixtures. A few reasons why the inclusion of recycled plastics into asphalt [is] attractive include: 1) low cost, 2) high availability and 3) properties that could be beneficial for pavement performance.

There is renewed interest in developing methods to beneficially use post-consumer waste plastic in highway construction. Previous research and development efforts have focused on addition of waste plastic to hot-mix asphalt pavements. The results of this prior research and development was not met with great success in the asphalt community primarily due to the incompatibility of common plastic and asphalt cement, which was manifested through poor laboratory performance. Compatibilization is a term used in polymer chemistry to describe a process where a substance is added to an immiscible blend of polymers to increase stability of the blended system. Besides creating a stable end-product, the resulting physical properties can be enhanced beyond the properties of each individual material. For the purposes of this research, compatibilization can be the addition of a third material to two immiscible materials or modification of one or both materials to provide for compatibility.

Texas

"Building Roads From Plastic Recyclables: With TxDOT Grant, UTA Team to Test Feasibility of Recycled Plastics in Road Construction," News Release, The University of Texas at Arlington, April 2020.
https://www.uta.edu/news/news-releases/2020/04/10/plastic-roads
From the news release: The University of Texas at Arlington researchers are combining their two areas of expertise—recycling and asphalt/concrete, respectively—to lead a two-year, $342,588 feasibility study on building plastic roads, funded by the Texas Department of Transportation (TxDOT). The roads wouldn't be made entirely of recycled plastic, but instead mixed with asphalt for an ideal consistency to keep the road safe for motorists and help it last longer, cost less and avoid cracking.
….
"Now that the international market for U.S. recycling materials no longer exists, we need to find and create local uses and markets for recycled plastics. TxDOT is focusing on increasing use of sustainable construction material, and this feasibility study of plastic roads is the agency's latest effort."

International Resources

Australia

"A Synthesis on the Effects of Two Commercial Recycled Plastics on the Properties of Bitumen and Asphalt," Greg White, *Sustainability*, Vol. 12, Issue 20, October 2020.
https://www.mdpi.com/2071-1050/12/20/8594/pdf
From the abstract: This synthesis combines the various research efforts to understand the effects of two commercially available recycled plastics, known as MR6 and MR10, on bituminous binders and asphalt mixtures. Using common test methods from the United Kingdom, the United States and Australia, generally consistent and significant effects were observed in various base bitumen grades and various common asphalt mixture types. Binder resistance to flow and binder elasticity both increased significantly and were associated with the three to four grade increases under the Performing Grading system. Similarly, mixture stiffness and mixture resistance to deformation increased significantly, while crack resistance and moisture damage resistance were not significantly affected. The effects of MR6 and MR10 were

generally similar to the effects associated with conventional polymer modification of asphalt binders and asphalt mixtures, particularly those effects associated with plastomeric polymers.

Viability of Using Recycled Plastics in Asphalt and Sprayed Sealing Applications, Christina Chin and Peter Damen, Austroads Ltd., October 2019.
https://www.level5design.com.au/uploads/1/2/4/6/124618711/ap-t351-19_viability_of_using_recycled_plastics_in_asphalt_and_sprayed_sealing_applications.pdf
From the abstract: This report examines the viability of using recycled plastics in asphalt and sprayed seals by Australian and New Zealand road authorities. The report presents the findings of a literature review, including case studies of local and overseas road trials. It finds that waste plastic can act as a partial aggregate replacement in bituminous mixes and a binder extender without having any significant influence on the properties of the asphalt mix. However, not all recycled plastics are suitable for bitumen modification at high temperatures. It also finds that while there may be environmental benefits associated with the use of recycled plastic, there are concerns regarding the potential health and safety hazards that road workers might be exposed to while handling these materials, sustainability impacts and impacts on the surrounding environment.

"Strength Evaluation of Utilizing Recycled Plastic Waste and Recycled Crushed Glass in Concrete Footpaths," Alireza Mohammadinia, Yat Choy Wong, Arul Arulrajah and Suksun Horpibulsuk, *Construction and Building Materials*, Vol. 197, pages 489-496, February 2019. Citation at https://trid.trb.org/view/1572001
From the abstract: This study entails incorporating recycled plastic waste (RPW) and recycled crushed glass (RCG) as coarse aggregate replacement in concrete mixture and to evaluate its feasibility as concrete footpath construction. The coarse aggregates in concrete were replaced by RPW and RCG aggregates in proportions of 0%, 10%, 20%, 30%, 40% and 50% was investigated. The properties of concrete evaluated in this study include uniaxial strength, tensile strength and capillary water uptake. Results from this investigation showed that incorporation of RPW and RCG in concrete can be a viable solution for the recycling of plastic waste and crushed glass in industrial applications. Although the compressive and splitting tensile strength values of the concrete samples containing RPW and RCG aggregate were found to be reduced due to low adhesion between the recycled aggregates and the cement gel matrix as well as low aggregate crushing resistance, coarse aggregate replacement were found to be still viable up to 20% by volume for RPW and up to 30% by volume for RCG for use in footpath construction.

"Laboratory Evaluation of Asphalt Containing Recycled Plastic as a Bitumen Extender and Modifier," Greg White and Connor Magee, *Journal of Traffic and Transportation Engineering*, Vol. 7, pages 218-235, 2019.
https://davidpublisher.org/Public/uploads/Contribute/5ddb2c76d3b73.pdf
From the abstract: Although significant field trials of waste plastic modified asphalt have been reported in Australia since 2017, no laboratory evaluation of the effects of these products on the engineering properties of binder and asphalt has been published. In this research, two commercially available recycled waste plastic products were evaluated in the laboratory. One product is intended to be plastomeric while the other is intended to be elastomeric in nature. Compared to unmodified viscosity grade bitumen and acid modified multigrade, the recycled plastic products increased the viscosity and softening temperature of the binder and introduced significant elastic recovery. Following dry-mixing into asphalt, the recycled plastic products were associated with improved mixture deformation resistance and increased mixture stiffness. However, the mixtures containing recycled plastic were also associated with an increase in moisture susceptibility and their fatigue lives were not significantly different to those of the control mixtures. Further research is recommended to better understand the modest reduction

in moisture damage resistance associated with recycled plastic, as well as the digestion of recycled plastic via the dry-mixing process.

"Waste Plastic as Additive in Asphalt Pavement Reinforcement: A Review," Nuha S. Mashaan, Ali Rezagholilou and Hamid Nikraz, *18th Australian Asphalt Pavement Association (AAPA) International Flexible Pavements Conference,* 2019.
http://railknowledgebank.com/Presto/content/GetDoc.axd?ctID=MjE1ZTI4YzctZjc1YS00MzQ4LTkyY2UtMDJmNTgxYjg2ZDA5&rID=OTYwNw==&pID=MTQ3Ng==&attchmnt=True&uSesDM=False&rIdx=MjAxMjg=&rCFU=
From the conclusions on page 7 of the PDF: Using waste plastic as [an] additive in asphalt reinforcement has shown significant improvement on its engineering properties, which enhances the modified asphalt resistance to rutting, fatigue, deformation and moisture stability. Based on data of previous studies, 4% of waste HDPE is recommended as [the] best content to achieve better asphalt performance properties in term[s] of stiffness and rutting resistance, however, other[s] had recommended waste PET up to 6[%]-8% as an ideal modifier that increase[s] fatigue life and, as such improve[s] the long[-]term performance and durability of the asphalt mixture.

"Recycled Waste Plastic for Extending and Modifying Asphalt Binders," Greg White and Gordon Reid, *8th Symposium on Pavement Surface Characteristics: SURF 2018—Vehicle to Road Connectivity*, 2018.
https://www.macrebur.com/pdfs/product/SURF%20-%20Plastic%20Recycling%20for%20Bitumen%20Ver%204.pdf
From the abstract: This paper assesses the use of three commercially available recycled plastic products for bituminous binder extension and modification in asphalt mixtures. Using a dry-mixing process, shredded and pelletised recycled waste plastics replace 6% of the binder volume. Comparative laboratory testing of two typical UK [United Kingdom] asphalt mixtures indicated that asphalt containing the recycled waste plastic products showed improved deformation resistance and fracture resistance compared to conventional 40/60 penetration grade binder. The viability of imported recycled plastic waste use in Australian asphalt mixtures was also evaluated. One of the three recycled plastic products is expected to be a cost effective alternate to M1000 or A35P and another is expected to be a viable alternate to A20E, at a significant cost saving. Partial replacement, without performance enhancement, of C320 bitumen is not viable due to the high cost of recycled waste plastic importation. However, partial C320 replacement may become viable with the introduction of local recycled plastic processing in the future. The findings of this research require validation by objective comparison to Australian asphalt mixtures produced with common Australian asphalt binders, as well as confirmation of likely importation costs. Verification of consistent product digestion and distribution through drum-based asphalt production plants is also required.

China

"Laboratory Evaluation of the Effect of Composite Modifier on the Performance of Asphalt Concrete Mixture," Weidong Cao, Shutang Liu and Xinxin Li, *Construction and Building Materials*, Vol. 155, pages 363-370, November 2017.
Citation at https://trid.trb.org/view/1485161
From the abstract: The composite modifier (CM) of asphalt concrete (AC) mixture containing crumb tire rubber, recycled plastic particles and SBS was developed. The main objective of this study was to evaluate the effect of CM on the performance of AC mixture. Wheel tracking test, beam bending test, freeze-thaw indirect tensile test and bending creep test of CM modified AC mixtures and the control mixture (AC mixture without CM) were conducted in laboratory. The results show the addition of CM in AC mixtures can significantly improve high temperature

performance compared to the control mixture, but the unsuitable dosage of CM may have some adverse effect on low temperature performance and moisture susceptibility. Considered comprehensively, the optimum dosage of CM was determined to be 0.3%. The relationship between the low temperature performance and CM dosage was verified by the m/S and dissipation energy ratios (Wd/Ws) calculated using Burgers model parameters of the bending creep at 0 °C. Compared to the control mixture, the values of permanent deformation and creep rate of CM modified AC mixture were smaller, and the values of the parameters E_1 and η_1 of Burgers model for the bending creep at 35 °C were larger. It can be further verified that the addition of CM obviously improves permanent deformation resistance of AC mixtures at high temperature.

"Impact Performance of Recycled Plastic-Based Concrete," Feng Liu, Yong Yan, Lijuan Li, Cheng Lan and Gongfa Chen, *Journal of Materials in Civil Engineering*, Vol. 27, Issue 2, February 2015.
Citation at https://trid.trb.org/view/1278533
From the abstract: This paper reports an experimental study on recycled plastic concrete (RPC) which uses recycled [a]crylonitrile-butadiene-styrene/[p]olycarbonate copolymer (ABS/PC) plastic particles to replace 5%, 10%, 15% and 20% (in volume) of fine aggregate sand. The plastic particles used in this research were recycled from waste plastic. The static and dynamic mechanical properties of specimens made of 5%, 10%, 15% and 20% plastic aggregate in volume were measured on MATEST24048 [Matest 24048] testing machine. The cube strength, axial compressive strength and static stress-strain relationship of the RPC specimens with different plastic content was obtained. The ultimate compressive strength, ultimate strain and dynamic stress-strain relationship of these specimens were measured by the device of Split-Hopkinson Pressure Bar (SHPB) under four different strain rates. The stress-strain curves and energy absorption of the RPC specimens with different plastic content was obtained under the four different strain rate levels[,] respectively. The influences of plastic content and strain rates on the mechanical property of RPC were analyzed. The results showed that the energy absorption capability of RPC was higher than that of normal concrete (NC) and increased with the plastic content. The impact resistance performance of RPC materials was superior to that of NC.

India

"Performance of Stone Matrix Asphalt and Asphaltic Concrete Using Modifiers," M.S. Ranadive, H.P. Hadole and S.V. Padamwar, *Journal of Materials in Civil Engineering*, Vol. 30, Issue 1, January 2018.
Citation at https://trid.trb.org/view/1486664
From the abstract: This paper proposes the use of fiber extracted from refrigerator door panels (FERD) and waste plastic in bituminous mixes for road construction. The effect of modification of bituminous mixes like stone matrix asphalt (SMA) and asphalt concrete (AC) with FERD and processed waste plastic in granular form was studied. The FERD was used to modify the SMA and AC, whereas waste plastic was used to modify AC. Different mixes of SMA and AC were prepared with and without filler material. Furthermore, the study was done with varying lengths of fibers (2, 4, 6 and 8 mm), which were added to the SMA and AC mixtures. Asphalt concrete mixtures with 0[%], 4[%], 6[%], 8[%], 10[%] and 12% waste plastic by weight of bitumen were prepared. The effect of the preceding on drain down, Marshall stability and indirect tensile strength was promising.

"Utilization of Waste Polymers for Flexible Pavement and Easy Disposal of Waste Polymers," R. Vasudevan, R. Velkennedy, A. Ramalinga Chandra Sekar and B. Sundarakannan, *International Journal of Pavement Research and Technology*, Vol. 3, Issue 1, pages 34-42, January 2010.
Citation at https://trid.trb.org/view/913370
From the abstract: Traffic intensity is increasing, as are load bearing capacities of the roadways. Studies on the improvement of road strength using polymer[-]modified bitumen for flexible pavement are being carried out by different schools. Virgin and recycled polymers are being used for these studies. However, when higher percentages of plastic wastes are used, the polymer becomes separated from the blend. Hence, a new innovative technique was developed by the authors and the heated stone aggregate was first coated with plastics generated from wastes like carry bags, films, foams and multi layers and the plastics waste coated aggregate (PCA) was used as the raw material for flexible pavement. PCA is then mixed with 60/70 or 80/100 bitumen and the mix is used for road construction. PCA + bitumen mix showed better binding properties, had less wetting properties and its voids were much less. The sample showed higher Marshall [s]tability value. By this process a road of 1 km length and 3.75 m width of single lane can consume 1,000,000 carry bags, road strength is increased by 100%, and there is no pothole formation. The roads laid using PCA + bitumen mixes are performing well. Performance studies were carried out for plastic road of different ages and are reported in this paper.

Iraq

"Optimum Use of Plastic Waste to Enhance the Marshall Properties and Moisture Resistance of Hot Mix Asphalt," Hamed M. Jassim, Omar T. Mahmood and Sheelan A. Ahmed, *International Journal of Engineering Trends and Technology*, Vol. 7, Issue 1, pages 18-25, January 2014.
https://www.ijettjournal.org/volume-7/number-1/IJETT-V7P223.pdf
From the conclusions that begin on page 7 of the PDF: On the basis of the materials used and laboratory tests performed in this study, the following conclusions can be stated:

1) The plastic waste derived from the different types and sizes of bottles can be utilized to modify the asphalt mixture performance if added to aggregate with a specific (size, thickness and content).
2) Adding fine size of shredded plastic waste particles (passing sieve No.16 (1.18 mm)) to the asphalt mixture increases Marshall stability and index of retained strength by 18% and 12%, respectively, as compared with the conventional mix.
3) The use of plastic waste particles size retained on sieve (3/8" (9.5 mm) and the upper sieves) decrease the Marshall stability and moisture resistance. This can be attributed to poor adhesion between the mixture components due to the presence of coarse plastic particles.
4) Using thick particles of plastic waste in asphalt mixture decrease the Marshall stability and increase moisture susceptibility as compared with using the thin particles.
5) The recommended proportion of the added plastic waste is up to 15% by weight of aggregate that can be used for construction of road pavement to improve the Marshall stability and moisture resistance.
6) The developed numerical models can be used as a guide to predict the effect of the plastic waste parameters on the performance of hot mix asphalt.

Italy

"Asphalt Surface Mixtures With Improved Performance Using Waste Polymers via Dry and Wet Processes," Mauro Ranieri, Liliana Costa, Joel R.M. Oliveira, Hugo M.R.D. Silva and Clara Celauro, *Journal of Materials in Civil Engineering*, Vol. 29, Issue 10, October 2017.
Citation at https://ascelibrary.org/doi/10.1061/%28ASCE%29MT.1943-5533.0002022
From the abstract: The mechanical performance of a typical surface course mixture, modified with two different plastic wastes, both via the wet and dry processes, was evaluated in this study. Water sensitivity, rutting resistance, stiffness modulus and fatigue cracking resistance tests were used. The results obtained indicated that the polymer-modified mixtures showed similar or improved performance when compared with that of a conventional control mixture produced with a harder virgin grade bitumen, not always available, or available at higher costs, in several countries. … Moreover, the mixtures produced via the dry process showed increased water sensitivity and stiffness modulus properties.

Saudi Arabia

"Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification," Muhammad A. Dalhat, Hamad Al-Abdul Wahhab and Khaleel Al-Adham, *Journal of Materials in Civil Engineering*, Vol. 31, Issue 8, August 2019.
https://www.researchgate.net/publication/333394962_Recycled_Plastic_Waste_Asphalt_Concrete_via_Mineral_Aggregate_Substitution_and_Binder_Modification
From the abstract: Several studies have focused on stone mastic asphalt concrete (SMA) or isolating recycled polyethylene terephthalate (RPET) as an aggregate substitute. In this study, a combined form of recycled plastic waste (RPW) was used as a mineral aggregate supplement in a dense-graded hot mix asphalt (HMA) AC made with RPW-modified asphalt binder. The term hybrid RPW-AC is used to refer to the HMA AC in this study. The viscoelastic performance of ACs containing combined RPW aggregates were compared with those containing RPET-only aggregates. Dynamic modulus (|E*|) tests, flow number (FN) tests and rutting resistance tests using an asphalt pavement analyzer (APA) were utilized to evaluate the performance of the hybrid RPW asphalt concrete mixes and were compared to fresh, RPET and crumb rubber AC. The results showed that combined RPW as an aggregate supplement has advantages over the use of RPET-only aggregates. The hybrid RPW-AC showed superior performance compared to the reference mixtures.

RIC 1, Polyethylene Terephthalate

<u>Domestic Resource</u>

"Mechanical Properties of Polyethylene Terephthalate Particle-Based Concrete: A Review," H. Ataei, K. Kalbasi Anaraki and Rui Ma, *International Conference on Highway Pavements and Airfield Technology*, pages 57-68, 2017.
Citation at https://trid.trb.org/view/1558702
From the abstract: Prior research results on mechanical properties of the PET concrete demonstrate that the strength of concrete decreases with increasing the PET replacement ratio. However, the toughness of PET concrete is higher than the normal concrete, which may extend its use in transportation and pavement engineering applications where impact and dynamic loads govern the design.

International Resources

China

"Effects of Waste Polyethylene on the Rheological Properties of Asphalt Binder," Qunshan Ye, Serji Amirkhanian, Jin Li and Zixuan Chen, *Journal of Testing and Evaluation*, Vol. 48, Issue 3, pages 1893-1904, May 2020.
Citation at https://trid.trb.org/view/1682863
From the abstract: The effects of waste polyethylene (PE) on the rheological properties of asphalt binder were investigated in this research. Three types of PE were adopted to prepare modified binders with contents ranging from 2[%] to 6%. A viscosity test, performance grade test, frequency sweep test, amplitude sweep test and linear amplitude sweep test are conducted to study rheological properties of PE[-]modified binders, compared with base binder and binders modified with styrene-butadiene-styrene and crumb rubber modifier. The test results indicated that the high temperature properties of asphalt binders could be effectively improved by the PE modifiers with different types and contents. The high temperature grade and rutting resistance factor of PE[-]modified binder can be increased significantly when compared with the base binder. With the increased PE content, the complex modulus increased, whereas the phase angle values decreased in most test frequencies and shear strain, which implied that the usage of PE not only reinforced the viscosity of binders but also enhanced the elasticity. The fatigue properties of PE[-]modified binders were improved, especially at the lower shear strain range. However, PE modifier had a negative effect for asphalt binder on low temperature property.

Nigeria

"Recycling of Polyethylene Terephthalate (PET) Plastic Bottle Wastes in Bituminous Asphaltic Concrete," Adebayo Olatunbosun Sojobi, Stephen Emeka Nwobodo and Oluwasegun James Aladegboye, *Civil and Environmental Engineering*, Vol. 3, Issue 1, January 2016.
https://www.cogentoa.com/article/10.1080/23311916.2015.1133480
From the abstract: … the effects of recycling PET plastic bottle wastes produced in North Central Nigeria in bituminous asphaltic concrete (BAC) used in flexible pavement construction were also evaluated. The mix design consists of 60/70 penetration-grade asphaltic concrete (5%), 68% coarse aggregate, 6% fine aggregate and 21% filler using the dry process at 170° C. The optimum bitumen content (OBC) for conventional BAC was obtained as 4% by weight of total aggregates and filler. Polymer-coated aggregate (PCA)-modified BAC seems preferable because it has the potential to utilize more plastic wastes with a higher optimum plastic content (OPC) of 16.7% by weight of total aggregates and filler compared to that of 9% by weight of OBC achieved by PMB [polymer-modified bitumen]-BAC. For both PMB- and PCA-modified BAC, an increase in air void, void in mineral aggregate and Marshall stability were observed.

Turkey

"An Approach to the Usage of Polyethylene Terephthalate (PET) Waste as Roadway Pavement Material," Metin Gürü, M Kürşat Çubuk, Deniz Arslan, S. Ali Farzanian and İbrahim Bilici, *Journal of Hazardous Materials*, Vol. 279, pages 302-310, July 2014.
https://www.researchgate.net/publication/264391182_An_approach_to_the_usage_of_polyethylene_terephthalate_PET_waste_as_roadway_pavement_material
From the abstract: Two novel additive materials, namely Thin Liquid Polyol PET (TLPP) and Viscous Polyol PET (VPP), were chemically derived from waste PET bottles and used to modify the base asphalt separately for this aim. The effects of TLPP and VPP on the asphalt and hot mix asphalt (HMA) mixture properties were detected through conventional tests (Penetration, Softening Point, Ductility, Marshall [s]tability, Nicholson Stripping) and Superpave methods

(Rotational Viscosity, Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR)). Also, chemical structures were described by Scanning Electron Microscope (SEM) equipped with Energy Dispersive Spectrometer (EDS) and Fourier Transform Infrared (FTIR) techniques. Since TLPP and VPP were determined to improve the low temperature performance and fatigue resistance of the asphalt as well as the Marshall [s]tability and stripping resistance of the HMA mixtures based on the results of the applied tests, the usage of PET waste as an asphalt roadway pavement material offers an alternative and a beneficial way of disposal of this ecologically hazardous material.

RIC 2, High-Density Polyethylene, and/or RIC 4, Low-Density Polyethylene

International Resources

Australia

"Stiffness Properties of Recycled Concrete Aggregate With Polyethylene Plastic Granules in Unbound Pavement Applications," Ehsan Yaghoubi, Arul Arulrajah, Yat Choy Wong and Suksun Horpibulsuk, *Journal of Materials in Civil Engineering*, Vol. 29, Issue 4, November 2016.
https://www.researchgate.net/publication/310391089_Stiffness_Properties_of_Recycled_Concrete_Aggregate_with_Polyethylene_Plastic_Granules_in_Unbound_Pavement_Applications
From the article's conclusions: In this research, two types of recycled waste materials, RCA [recycled concrete aggregate] and polyethylene plastic blends (HDPE and LDPE), were evaluated for their stiffness and resilient characteristics. Because the polyethylene plastics in this research were used in the form of granules instead of reinforcing fibers, a slight degradation of RCA properties was observed. The following results are obtained from the outcomes of this research:

- Samples prepared by adding 3% and 5% LDPE or HDPE yielded CBR [California bearing ratio] values comparable to those of typical quarry materials, and these blends could be used in base and subbase layers. Blends of RCA–HDPE showed higher CBR values.
- Specimens containing HDPE particles showed greater UCS [unconfined compressive strength] values and higher Young's moduli compared with LDPE blends. SEM images showed there was no significant difference in roughness of HDPE and LDPE particle surfaces; this could be attributed to the lower sphericity of LDPE particles compared with the cylindrical shape of HDPE particles. Generally, a greater plastic content results in lower stiffness parameters of specimens, including E, E_{50} and v values.
- RCA–HDPE specimens presented higher resilient moduli due to higher E values and the cylindrical shape of HDPE particles. Similar to the stiffness parameters, M_r values of the specimens decreased by increasing the plastic content due to further replacement of rough-surfaced materials (RCA) with smooth surfaced particles (HDPE and LDPE).
- RLT [repeated load triaxial] test results showed that M_r values of all four types of specimen fall within the range of typical quarry materials. Moreover, the evaluation of the results using the resilient modulus models showed that the percentage of plastic particles did not affect the geotechnical nature of RCA. As a result, RCA–HDPE and RCA–LDPE blends can be used in pavement bases and subbases.

China

"Pavement Properties of Asphalt Modified With Packaging-Waste Polyethylene," Changqing Fang, Caixia Wu, Jingbo Hu, Ruien Yu, Zengping Zhang, Long Nie, Shisheng Zhou and Xinghua Mi, *Journal of Vinyl and Additive Technology*, Vol. 20, Issue 1, pages 31-35, March 2014.
https://fdocuments.us/document/pavement-properties-of-asphalt-modified-with-packaging-waste-polyethylene.html
From the abstract: Recycled packaging-waste polyethylene (WPE) was used to replace the ordinary polymer modifier in the modification of raw asphalt, and the pavement properties of the modified asphalt were studied. The high-temperature stability, anti-cracking properties at low temperature, life span, and stability against water of the asphalt mixture were improved, a finding which is attributed to the properties and characteristics of WPE, the swelling of sheared WPE, and the WPE/asphalt network structure. The use of packaging WPE can improve the pavement properties of asphalt, as well as save resources and reduce white pollution.

India

"Plastic Roads: Use of Waste Plastic in Road Construction," Ahmed Trimbakwala, *International Journal of Scientific and Research Publications*, Vol. 7, Issue 4, pages 137-139, April 2017.
http://www.ijsrp.org/research-paper-0417/ijsrp-p6424.pdf
From the introduction on page 1 of the PDF: By mixing plastic with bitumen the ability of the bitumen to withstand high temperature increases. The plastic waste is melted and mixed with bitumen in a particular ratio. Normally, blending takes place when temperature reaches 45.5° C but when plastic is mixed, it remains stable even at 55° C. The vigorous tests at the laboratory level proved that the bituminous concrete mixes prepared using the treated bitumen binder fulfilled all the specified Marshall mix design criteria for surface course of road pavement. There was a substantial increase in Marshall [s]tability value of the BC [bituminous concrete] mix, of the order of two to three times higher value in comparison with the untreated or ordinary bitumen. Another important observation was that the bituminous mixes prepared using the treated binder could withstand adverse soaking conditions under water for longer duration.

"Plastic Roads: A Recent Advancement in Waste Management," Huda Shafiq and Anzar Hamid, *International Journal of Engineering Research and Technology*, Vol. 5, Issue 9, pages 684-688, September 2016.
https://doi.org/10.17577/ijertv5is090574
From the literature review on page 2 of the PDF: Considerable research has been carried out to determine the suitability of plastic wastes in the construction of bituminous pavements. Dr. R. Vasudevan has stated in his works that the use of plastic in bitumen improves the binding properties of bitumen. Prof. C.E.G Justo states that addition of 8% percent by weight of processed plastic is desirable in saving 0.4% bitumen by weight of mix as it improves the stability, strength, life and other desirable properties of bitumen. Dense bituminous macadam with recycled plastics, mainly low[-]density polyethylene (LDPE) replacing 30% of 2.36 – 5 mm aggregates, reduced the mix density by 16% and showed 250% increase in Marshall [s]tability. Zoorab and Suparma stated that the use of recycled plastics in plain bituminous concrete mixes increases its durability and fatigue life. D.N. Little further worked on the effect of plastics on bitumen and found the resistance to deformation of asphaltic concrete modified with low[-] density polyethylene (LDPE) was reasonably improved. Studies have showed that the use of recycled polyethylene in bituminous pavement mixes reduces the permanent deformation in the form of rutting and the low temperature cracking of pavement surfacing. Bindu et al. studied the

effects of shredded plastic in stabilizing the stone mastic asphalt (SMA) mixture in flexible pavements.

"Effect of Waste Plastics Utilization on Indirect Tensile Strength Properties of Semi Dense Bituminous Concrete Mixes," M.R. Archana, H.S. Sathish, M. Ashwin and Hanamant Hunashikatti, *Indian Highways*, Vol. 42, Issue 2, pages 69-78, February 2014.
Citation at https://trid.trb.org/view/1306785
From the abstract: This paper calls for the use of plastic in bituminous concrete to get improved properties which can cater to increasing traffic intensity, for the study [of] semi[-]dense bituminous concrete grading 2 as per Ministry of Road Transport & Highways (MoRT&H) (IV Revision), 60/70 grade bitumen and 40 micron[-]sized plastic were used. Aggregate and binder were checked for their suitability through various basic tests. Marshall tests, indirect tensile strength tests and degradation tests were conducted with trial waste plastic content added along with aggregates to find the influence of plastic addition to semi[-]dense bituminous concrete mix.

Portugal

"Incorporation of Waste Plastic in Asphalt Binders to Improve Their Performance in the Pavement," Liliana M.B. Costa, Hugo M.R.D. Silva, Joel R.M. Oliveira and Sara R.M. Fernandes, *International Journal of Pavement Research and Technology*, Vol. 6, Issue 4, pages 457-464, July 2013.
https://www.academia.edu/34288542/Incorporation_of_Waste_Plastic_in_Asphalt_Binders_to_Improve_their_Performance_in_the_Pavement
From the article's conclusions: The suitability of using different types of polymers (granulated and in powder) in the bitumen modification was evaluated in this study, in particular to assess the potential [for] using recycled polymers in asphalt mixtures for their valorization. The studied polymers were EVA [ethylene-vinyl acetate] (virgin and recycled), SBS (virgin), HDPE (recycled), LDPE (recycled), ABS [acrylonitrile-butadiene-styrene] (recycled) and crumb rubber from used tires (recycled). The characterization of the different bitumens modified with 5% of each one of the studied polymers demonstrated that it is possible to obtain similar properties, or even better, than those of a commercial modified bitumen. In fact, it was observed that:

- SBS, HDPE and EVA are the most promising polymers to increase the softening point of the modified binder;
- HDPE and EVA are the polymers with higher influence in the penetration test results;
- SBS, EVA and crumb rubber (elastomers) presented the best performance in relation to resilience (elastic recovery after penetration);
- [A]ll modified bitumens, excluding those with ABS and crumb rubber, only reach the proper viscosity to produce asphalt mixtures near or above 180 °C, including the commercial bitumen;
- HDPE, LDPE and EVA have a good digestion in the bitumen, whereas SBS, ABS and rubber are difficult to be melted in the bitumen (they should be milled to optimize their effectiveness).

Spain

“Use of Plastic Wastes From Greenhouse in Asphalt Mixes Manufactured by Dry Process,” J.E. Martin-Alfonso, A.A. Cuadri, J. Torres, M.E. Hidalgo and P. Partal, *Road Materials and Pavement Design*, Vol. 20, Supplement 1, pages S265-S281, April 2019.
Citation at https://trid.trb.org/view/1607360
From the abstract: This work assesses the applicability of low[-]density polyethylene (LDPE), recycled from greenhouses used in agriculture, as a modifier of asphalt mixes manufactured by a dry process. To that end, a comprehensive laboratory study was conducted to design different asphalt mixes, formulated with recycled plastic, according to the European standards. Additionally, recycled plastic (LDPE_R) has been modified by compatibilizing agents (bitumen and oil) as a way to facilitate plastic incorporation into the mix. Results showed unmodified and modified plastics lead to bituminous binders with enhanced viscous and viscoelastic properties at medium-high in-service temperatures compared to a reference sample (PMB45/80-65). Plastic (and modified plastic) addition to AC asphalt mixes has enhanced mix behaviour associated to water sensitivity and rutting resistance. For high modulus asphalts MAM [MAM is a high modulus mix type in the Spanish specifications], the incorporation of plastics considerably improves the water sensitivity and fatigue resistance. Finally, BBTM [Béton Bitumineux Très Mince, a thin surfacing layer] mixes with added LDPE met technical requirements requested by Spanish regulations. However, compared to a mix manufactured with a PMB 45/80-65, plastic addition led to a poorer mix performance in term of particle loss and, above all, fatigue resistance.

United Kingdom

“Modification of a 14mm Asphalt Concrete Surfacing Using RAP and Waste HDPE Plastic,” Imam Aschuri and David Woodward, *International Journal of Pavements*, Vol. 9, Issue 1-2-3, pages 70-78, 2010.
Citation at https://trid.trb.org/view/1147600
From the abstract: This paper reports the findings of a laboratory investigation to assess the use of waste high-density polyethylene (HDPE) plastic and recycled asphalt pavements (RAP) to improve the performance of a 14 mm asphalt concrete (AC) surfacing. Waste HDPE plastic obtained from plastic milk cartons was blended with 60/70 penetration grade bitumen and its addition evaluated using the Softening Point test and modified Penetration test at 25° C, 30° C, 35° C and 40° C. This found the addition of waste HDPE plastic to increase softening point and lower penetration value. Deformation and fatigue testing of a 14 mm asphalt concrete mix surfacing mix incorporating a blend of waste HDPE plastic and RAP was carried out at a range of test temperatures. This found that modification using waste HDPE plastic and RAP improved both deformation and fatigue properties. The laboratory investigation has shown that the use of waste HDPE plastic derived from milk containers combined with RAP could improve the performance of asphalt concrete subjected to heavy trafficking at higher ambient temperatures.

RIC 2, High-Density Polyethylene; RIC 4, Low-Density Polyethylene; and RIC 5, Polypropylene

International Resources

India

"A Study on the Plastic Waste Treatment Methods for Road Construction," Maaz Allah Khan, Raghvendra Bajpai, Maaz Allah Khan, Pramod Kumar Yadav and Pawan Kumar Srivastava, *International Journal of Advance Research, Ideas and Innovations in Technology*, Vol. 3, Issue 6, 2017.
https://www.ijariit.com/manuscripts/v3i6/V3I6-1323.pdf
From the abstract: The experimentation at several institutes indicated that the waste plastic, when added to hot aggregate will form a fine coat of plastic over the aggregate and such aggregate, when mixed with the binder is found to give higher strength, higher resistance to water and better performance over a period of time.

Saudi Arabia

"Performance of Recycled Plastic Waste Modified Asphalt Binder in Saudi Arabia," M.A. Dalhat and H.I. Al-Abdul Wahhab, *International Journal of Pavement Engineering*, Vol. 18, Issue 4, pages 349-357, April 2017.
Citation at https://doi.org/10.1080/10298436.2015.1088150
From the abstract: The effect of polypropylene, high- and low-density polyethylene (PP, HDPE and LDPE)-recycled plastic wastes (RPW) on the viscoelastic performance of the local asphalt binder has been investigated. The recycled plastics were obtained by shredding and grounding the RPW to a desirable size for easier blending with the asphalt binder. All the RPWs result in an improved rutting performance. The RPW-modified asphalts upper PG [performance grade] limit increase by at least one level for each 2% increase in the RPW content, in most cases. An increase of 55[%], 19[%] and 9% in resilient modulus (MR) was observed for PP-, HDPE- and LDPE-produced asphalt concrete (AC), respectively. Correlation between the M_R of the AC and non-recoverable creep compliance (J_{nr}) of the asphalt binder was established. The obtained viscoelastic properties of the RPW-modified binder was utilised to model a typical pavement section using AASHTO mechanistic empirical pavement design guide (ME-PDG) software. The predicted distresses of the modelled pavement shows significant rutting and fatigue performance improvement for pavement produced with the RPW. Elastomeric type of polymer is required to supplement these RPW to enable them [to] meet the AASHTO TP 70 elastic recovery requirement.

RIC 6, Polystyrene

International Resource

India

"Development of Ecofriendly Concrete Incorporating Recycled High-Impact Polystyrene From Hazardous Electronic Waste," K. Senthil Kumar and K. Baskar, *Journal of Hazardous, Toxic and Radioactive Waste*, Vol. 19, Issue 3, pages 559-566, July 2015.
Citation at https://trid.trb.org/view/1357644
From the abstract: … this study was carried out using the recycled computer plastic waste as coarse aggregate in concrete. The computer plastic waste was collected and made into chips, which predominantly have high[-]impact polystyrene (HIPS). The coarse aggregate was partially replaced with HIPS by volume percentages of 10[%], 20[%], 30[%], 40[%] and 50% for different

water-cement ratios such as 0.53, 0.49 and 0.45. A total of 486 concrete specimens were cast to investigate the effect of HIPS and water-cement ratio on the fresh and hardened properties of concrete. The concrete specimens were tested under compression, tension and flexure on the 7th and 28th day. The engineering properties such as workability, compressive strength, flexural strength, split tensile strength and elastic modulus of concrete were obtained experimentally and were compared with the control concrete. From the experimental results, concrete specimens made using HIPS aggregate were found to be capable of retaining 50% strength under all of the test conditions, when 50% coarse aggregates are replaced by HIPS aggregate. Various volume percentages of HIPS aggregate replacement show a linear relation between the loss of strength and increase in HIPS content. Because the reduction in strength was observed, this type of concrete can be used in nonstructural elements such as partition walls and lightweight roofs. The addition of HIPS aggregate in concrete reduces the unit weight of concrete; it can be used in earthquake-prone areas where the reduction in mass is essential.

Commercial Suppliers

Cited below are web sites and publications associated with commercial suppliers of materials that employ recycled plastics in pavement applications:

- *Dow* (Midland, Michigan). Dow has completed two small projects on private roads in Texas and a recycled plastics application on a public road in Michigan. The Texas projects used asphalt binders modified with recycled plastics that employed a wet process that used binder modified with 1.5% linear low-density polyethylene post-consumer plastics, Elvaloy copolymer and polyphosphoric acid.
- *MacRebur Ltd.* (Lockerbie, United Kingdom). MacRebur provided the paving material used for a University of California San Diego test site described on page 17. MacRebur uses a dry-mixing process to produce three products that use shredded and pelletized recycled waste plastics to replace a percentage of the binder volume. Binder replacement for these products is in the range of 6% to 10%, with 6% recommended as optimal.
- *PlasticRoad* (Vianen, Netherlands).The PlasticRoad consortium produces a prefabricated, modular and hollow road structure based on recycled plastics.
- *TechniSoil Industrial LLC* (Redding, California). TechniSoil technology was used in the Caltrans District 3 Highway 162 pilot project described in the news release cited on page 16. The company's web site describes its process as a modification of cold-in-place recycling, with a recycling "train" of equipment milling the existing roadway to crush and size the RAP. The RAP is then mixed with TechniSoil's G5 liquid plastic polymer binder, which is made in part of discarded plastic bottles, and the recycled mixture is immediately paved back onto the roadway.

Dow

"Dow Completes Roads Improved With Recycled Plastic: Pilot Circular-Economy Project Demonstrates Innovative Use for Post-Consumer Plastic," Press Release, Dow, February 26, 2019.
https://corporate.dow.com/en-us/news/press-releases/dow-completes-roads-improved-with-recycled-plastic.html
From the press release: As part of Dow's commitment to reducing plastic in the environment and delivering circular economy solutions through innovation, the company constructed two new

polymer modified asphalt (PMA) roads by improving them with post-consumer recycled plastic (PCR) at its Freeport, Texas[,] facility. Both private roads—Plastics Road and Gulfstream Road—are now open for traffic.

Enabled by DuPont Elvaloy asphalt modification technology, these roads achieved the following:

- Used 1,686 pounds of recycled linear low-density polyethylene (LLDPE) plastic—the equivalent weight of 120,000 plastic grocery bags.
- Covered a combined length of approximately 2,600 feet.
- Saved PMA material cost.
- Met Performance Grade 70-22 requirements.

Related Resources:

"Central Asphalt Constructs First Public Recycled Plastic Roads in U.S.: Dow Tests Recycled Plastic in Michigan Asphalt Roads," Allan Heydorn, ForConstructionPros.com, October 22, 2019.
https://www.forconstructionpros.com/pavement-maintenance/article/21093568/roads-using-recycled-plastic-built-in-michigan
From the online article: In August Dow Chemical Company announced the completion in Michigan of the first public asphalt road in the United States paved using a recycled plastic modified asphalt. The project, completed by Central Asphalt, Mt. Pleasant, MI [Michigan], was comprised of four public roads and a private parking lot on the Dow's facility in Midland, MI. The effort is the second phase of Dow's tests using recycled plastic in asphalt pavement in North America.

Dow had already tested its recycled plastic modified asphalt on two roads, Plastics Road and Gulfstream Road, at the chemical company's Lake Jackson campus in Freeport, TX [Texas]. Placed in February 2019, that project included 2600 ft. of a two-lane road around one of Dow's polyethylene plastic manufacturing plants.

"Recycled Plastics for Performance Graded Asphalts," C.J. DuBois, Hayley Brown, Rishi Munj and Cristina Serrat, Dow Texas Innovation Center, July 2019.
https://www.dow.com/en-us/document-viewer.html?ramdomVar=5894697877015346608&docPath=/content/dam/dcc/documents/en-us/tech-art/914/914-331-01-recycled-plastics-for-performance-graded-asphalts.pdf
This presentation provides data on the company's experimental use of waste plastics in asphalt.

MacRebur Ltd.

Roads: Using Waste Plastics to Enhance Our Road Networks, MacRebur Ltd., 2020.
https://www.macrebur.com/services/roads
From the web page: MacRebur plastic roads are everywhere from Aberdeenshire to Yorkshire in the UK and around the world from Australia to Bahrain. Our products have been used in asphalt on motorways, roundabouts, even airport runways and racetracks. MacRebur plastic roads look exactly the same as regular asphalt and require no change in the installation process. These roads have been extensively tested and monitored for over the last 3 years. After the success of these trials, the UK Department for Transport has earmarked £1.6m to extend the use of plastic roads in Cumbria.

Products, MacRebur Ltd., 2020.
https://www.macrebur.com/the-product
From the web site:

> MacRebur products are used as binder extenders and/or modifiers to reduce the volume of bitumen required in an asphalt mix, at the same time enhance or maintain asphalt performance.
>
> All products are made from 100% waste plastics that would otherwise go to landfill or incineration. Independent laboratory testing has demonstrated that MacRebur products do not leach plastic or generate toxic fumes.
>
> MacRebur products have been demonstrated by various laboratories across the world to significantly improve the stiffness and deformation resistance of asphalt whilst avoiding the embrittlement of oxidisation, evidenced by increased fracture toughness and fatigue life.

This web page provides access to a wide range of product-related resources:

Product

- MacRebur pavement improvement.
- Comparing to SBS PMB.
- Deformation resistance.
- Fracture resistance.
- Fume generation.
- Leaching.
- Marshalls.
- Moisture damage resistance.
- Product form change.
- Production consistence.
- Stiffness.
- MR6, MR8, MR10 product sheet.

Environmental

- Laboratory evaluation of asphalt containing recycled plastic as a bitumen extender and modifier (cited on page 20).
- Evaluating recycled waste plastic modification and extension of bituminous binder for asphalt paper.
- Recycled waste plastic for extending and modifying asphalt binders paper (cited on page 21).
- Recycled waste plastic modification of bituminous binder paper.
- Evaluation of MacRebur recycled plastic for bitumen extension and modification in asphalt presentation.
- Do microplastics from the road get washed off into the environment?

PlasticRoad

PlasticRoad, KWS (part of VolkerWessels), Wavin (part of the Mexichem group) and Total, undated.
https://www.plasticroad.eu/en/
From the web page:

> Prefabricated and modular
> The PlasticRoad concept consists of a prefabricated, modular and hollow road structure based on (recycled) plastics. The prefabricated production, the light weight and the modular design of the PlasticRoad make construction and maintenance faster, simpler and more efficient compared to traditional road structures.

Hollow design
The [PlasticRoad] has a hollow space that can be used to (temporarily) store water, thus preventing flooding during extreme precipitation. The hollow space can also be used for the transit of cables and pipes, thus preventing excavation damages. And there are numerous other conceivable applications, including the installation of sensors or the electric charging of vehicles.

Sustainable
The PlasticRoad is a completely circular product that is based on recycled plastics. It has a significantly smaller carbon footprint than traditional road structures thanks to the longer lifespan and the reduction of transport movements involved in its construction.
….

After a lot of research, lab tests and internal pilots, the first PlasticRoad in the world was opened on September 11th, 2018. The municipality of Zwolle and the province of Overijssel (NL) [Netherlands] together are the launching customers of the PlasticRoad. The first pilot is a bike path of 30 meters.

TechniSoil Industrial LLC

100% Road Recycling With G5, TechniSoil Industrial LLC, 2020.
https://technisoilind.com/technisoil-roads.html
From the web page: Our breakthrough G5 binder represents a major step forward in road recycling technology. We recycle 100% of the existing road in place, and approximately 150,000 plastic bottles per lane mile. The end result is a completely new category of plastic pavement.

Roads made with G5 possess the strength of concrete and the flexibility of asphalt.

Performance advantages include*:

- Lasts 2 - 3X longer than asphalt
- 5X the tensile strength of asphalt with increased flexural properties
- Zero flow (test finally aborted at 20,000 cycles)
- Compressive strength similar to concrete
- Eliminates rutting and provides extremely high reflective cracking resistance
- Delivers at least 50% life cycle savings to taxpayers
- Material can serve as a wearing course

* Conservative estimates cited. Lab tests conducted at the University of Nevada Reno demonstrate life cycle gains 6-13 times greater than traditional asphalt. As technology and construction continues to advance, we expect to realize optimized gains in all areas.

Related Resources:

Evaluation of TechniSoil G5 Stabilized Aggregate Mixture, TechniSoil Global Inc., December 2016.
https://technisoilind.com/pdf/UNR-Evaluation-of-TechniSoil-G5-Stabilized-Aggrgate-Mixture.pdf
From the executive summary: The TechniSoil G5 stabilizer is a polymeric binder that can be used for binding aggregates together to create a stable surface mixture for roadways and parking lots. Polymer products are partially derived from renewable resources such as plants and animals and, with some exceptions, generally do not contain toxins or

environmentally damaging substances. By using such polymer-based products, the use of toxic substances released to the environment can be reduced or eliminated and keep the world sustainable and green for future generation.

This report presents the results of a comprehensive laboratory evaluation program of a G5-stabilized aggregate mixture using the latest advancements in materials testing. Aggregates from Greenhorn were stabilized with TechniSoil G5 at a rate of 7.0% by dry weight of aggregates. The G5-stabilized aggregate mixture was evaluated for stiffness using the dynamic modulus (E*) test in accordance with AASHTO TP 79 and AASHTO PP 61, resistance to rutting using the flow number (FN) test in accordance with AASHTO TP 79, resistance to reflective cracking using the overlay tester (OT) in accordance with Tex-248-F, resistance to thermal cracking using the Uniaxial Thermal Stress and Strain Tester (UTSST) in accordance with an ASTM draft standard test method, and resistance to fatigue cracking using the flexural beam fatigue test in accordance with AASHTO T 321.

….

In summary, the G5-stabilized aggregate mixture exhibited unique characteristics with superior performance at high, intermediate and low temperatures suggesting a very good performance in the field when used as a surface course layer. The mixture may offer excellent alternatives when used as a surface layer in hot climate areas with heavy traffic and/or braking actions such as at traffic lights on urban streets and off-ramps. The mixture is also anticipated to perform very well when used in cold climates and/or on top of a cracked asphalt pavement due to its high resistance to reflective cracking and thermal cracking.

Agenda: Transportation Committee, South Bay Cities Council of Governments, November 2019.
https://www.southbaycities.org/sites/default/files/transportation_committee/November%202019%20Transportation%20Committee%20Agenda%20Packet.pdf
From page 5 of the agenda, page 11 of the PDF:

> **Los Angeles City To Test "Plastic Asphalt["]**
> Now that China has stopped accepting waste from California and lawmakers rejected a bill to phase out single-use plastic containers last September, L. A. City is getting more creative with its recycling solutions. In partnership with Techni[S]oil, owner of the patented product, the city will soon be testing a new paving material made largely out of recycled plastic. The city's Department of Street Services predicts the new material will reduce costs by 25[%], may be seven times stronger than regular asphalt, and will require significantly less maintenance. Plastic asphalt is made by converting shredded recycled plastic into an oil that replaces petroleum-based bitumen to become the binder in an otherwise traditional method of street pavement. Plastic roads may be more durable—up to seven times stronger than regular asphalt—and will require significantly less maintenance. The first test site—at West First Street and North Grand Avenue, near the Frank Gehry-designed Walt Disney Hall—will receive the treatment before the end of the year. The first test will include analysis to ensure that there is no adverse environmental impact from the plastic leaching into the stormwater system. Los Angeles is the first city in the U.S. to consider implementing this material on a wide scale, but the patented plastic road material has already been implemented in the U.K. and Australia.

Consultation With Selected Experts

To supplement literature search findings, CTC contacted experts expected to have knowledge of or experience with the use of recycled plastic in asphalt and concrete applications. Contact information for these experts appears on page 38.

State Agencies

CalRecycle

CTC convened a discussion with CalRecycle staff members about the use of recycled plastics in asphalt and concrete pavements. Staff members participating in this discussion:

- Robert Contreras, Environmental Scientist
- Nathan Gauff, Waste Management Engineer
- William Heung, Senior Waste Management Engineer
- Danielle Osborne, Environmental Scientist
- Kyle Pogue, Environmental Program Manager I

In addition to CalRecycle's expertise in the use of recycled plastics, the agency has a significant level of experience evaluating the use of waste tires in pavement applications and has found that crumb rubber from recycled tires provides better performance. CalRecycle staff members voiced concern that a movement away from the current diversion of scrap rubber for use in pavement applications to use of plastics classified as RIC 1 or RIC 2, which are easily recycled using other means, will upset current plastics recycling streams. CalRecycle's May 2020 waste characterization study cited on page 17 provides details of California's waste stream that can inform current and future recycling practices.

The CalRecycle team noted that there is little domestic research on the use of waste plastics in asphalt, and commercial supplier claims of strength and other benefits of the use of plastic in paving materials require further review. CalRecycle staff members recommended considering a range of issues as public agencies contemplate the use of plastic in pavement applications:

- Understand the impact on current plastic recycling streams for RIC 1 and RIC 2 plastics, which already have established markets for recycling.
- Consider the impact of displacing current practices for rubber recycling and reuse in pavement applications.
- Understand plastic's impact on pavement performance.
- Investigate the environmental impacts associated with the potential for plastic used in asphalt to move from the roadway into the environment.
- Consider other environmental issues, including whether asphalt made with plastic can be safety recycled after reaching its useful life.

Academic Institutions

California State University, Chico

CTC contacted DingXin Cheng, director of the California Pavement Preservation Center at California State University, Chico, to discuss his experience with the use of recycled plastics in pavement applications.

Cheng noted the use of RIC 1 and RIC 2 plastics at pilot sites in California and Texas. (Information about these pilot sites is available on pages 16 and 31, respectively.) He noted, as did the CalRecycle team, that extending the use of plastics in pavement applications to other RICs may be more useful because other RICs are harder to reuse.

Echoing the feedback provided by CalRecycle staff members, Cheng noted that domestic research in this area is limited, and both field and laboratory research would be beneficial. (California Pavement Preservation Center expects to conduct research in this area in 2021/2022.) Topic areas recommended for future research:

- The effectiveness of the dry versus wet processing method.
- The impact of plastic on pavement performance and how its performance compares to rubberized asphalt.
- The viability of using recycled plastics to introduce plasticity in order to make pavement more movable and improve mechanical performance.
- The effectiveness and environmental impact of recycling pavements incorporating plastics at an early age (after seven to 10 years of use).
- Other environmental considerations, such as the best blending temperature to limit emissions.

Contacts

CTC contacted the individuals below to gather information for this investigation.

State Agencies

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California Department of Resources Recycling and Recovery
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Nathan Gauff
Waste Management Engineer
California Department of Resources Recycling and Recovery
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