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**Recycling Waste
Plastics in Asphalt
Pavements**

**NATIONAL
ACADEMIES** *Sciences
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Recycling Waste Plastics in Asphalt Pavements

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Preface

This E-Circular captures information exchanged during the 99th Annual Meeting of the Transportation Research Board in Technical Session 1113: Plastics in Asphalt. Ben Cox of the U.S. Army Corps of Engineers presided over the session, which was sponsored by the Standing Committee on Production and Use of Asphalt (AKM10) and cosponsored by the Standing Committee on Resource Conservation and Recovery (AMS20). This E-Circular also captures some additional research information that was not originally presented in the technical session. Thanks are due to all who presented in the technical session as well as those who worked to prepare the information contained in this publication.

This E-Circular bears special significance to the members of the Standing Committee on Production and Use of Asphalt as it lamentably marks one of Dr. Rebecca (Becky) S. McDaniel's final contributions to the committee. Becky's contributions to the Committee are many, as are her contributions to the Transportation Research Board and the asphalt industry at large. Becky left lasting impacts, both on the global understanding of pavements and on all those who were fortunate enough to know her personally, and her smile and warm personality is greatly missed among the asphalt community. The members of the committee are honored to dedicate this E-Circular to Becky's legacy and memory.



In memory of Dr. Rebecca S. McDaniel.

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Introduction

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The increasing volume of plastic waste generated each year is a global problem—one that has been magnified following the 2017 passing of China's Operation National Sword policy that ended the import of waste plastics into the country effective January 2018. Rightfully, this action has awakened a renewed effort to reduce and recycle plastic waste and asphalt pavements have been identified as a potential new end market opportunity.

The asphalt industry has a prolific legacy of recycling numerous waste materials into asphalt pavements and is also no stranger to using plastics for modification of asphalt binders and mixtures as illustrated in Williams et al. (1) and Yin et al. (2). However, recycling of some materials has been more successful than others. Historical experiences with recycling plastics have documented limitations and challenges that will need to be considered or overcome for successful use in asphalt pavements, but the industry is eager to investigate its viability.

A key consideration is that recycling plastic in asphalt should not be performed solely for the sake of recycling, since this approach neglects economics, other environmental factors, and performance of national transportation infrastructure. A new paradigm is needed—not to simply recycle for the sake of recycling, but to recycle responsibly. As documented by Willis and Howard (3) for the cases of recycled tire rubber, recycled asphalt shingles, and reclaimed asphalt pavement, logical decisions rooted in data-driven engineering, science, and economics have yielded responsible practices, whereas recycling without proper engineering and science, as well-intentioned as it may be, can have consequences culminating in reduced pavement lifespans.

To disseminate information related to recycling waste plastics in asphalt pavements, a technical session was held at the 99th Annual Meeting of the Transportation Research Board in 2020. This session was organized to provide: (1) historical perspectives on modification of asphalt, including modification with virgin or recycled plastics, (2) chemical, rheological, and

mechanical data on recycled plastic-asphalt binder blends and mixtures, and (3) case studies where the “wet” or “dry” process was used to incorporate recycled plastic.

A driving motivation behind this technical session was to promote the concept that data-driven engineering should inform decisions on recycling plastics. Presenting state of the knowledge information and identifying technology gaps and challenges serves to guide future research in the pursuit to maximize effective and responsible recycling of plastic waste in asphalt.

All presenters in the technical session were invited to contribute to this E-Circular. This publication also contains additional research information that was not originally presented in the technical session. All included information serves to document challenges moving forward but also successes to date and promising results. Collectively, the information herein portrays a message of cautious optimism moving forward as well as the need for patience to allow research to propel rational and responsible engineering.

RECOGNITION OF DR. REBECCA S. MCDANIEL

Dr. Rebecca S. McDaniel, or simply, Becky, delivered the opening presentation in the technical session with an introductory overview and history of plastics in asphalt. Sadly, Becky’s presentation in this session was one of her final contributions to Transportation Research Board (TRB) and the Standing Committee on Production and Use of Asphalt as noted in the Preface. Considering her unexpected passing, this condensed introduction has been prepared on her behalf with Becky included as a contributing author.

Becky was a gifted engineer and keenly skilled at conveying information; this introduction will never quite be complete without Becky’s own words. Nevertheless, we are honored to pick up the baton where she left it, and we dedicate this document to her memory.

OVERVIEW OF ASPHALT MODIFICATION AND PLASTICS

Asphalt modification has been utilized for decades to engineer asphalt binders with enhanced properties relative to the original neat binder. Polymer modification dates back to the early- to mid-1900s in Europe and the mid-1900s in the United States. From the 1980s on, modification usage in the United States increased, and it is now a commonplace tool for engineering durable pavements such as high-traffic interstates or heavily loaded airfields.

Table 1 outlines a general additive classification system developed in the 1980s (4–6). Today, most common asphalt modifiers, such as styrene-butadiene-styrene (SBS), generally fall in Group 3. However, Table 1 serves to illustrate that plastics (Group 4) have long been considered when it comes to asphalt modification as further described in this E-Circular. Plastics have been used in practice to an extensive, though not necessarily widespread, degree such as in the patented Novophalt system used in the 1980s and 1990s (7–8).

While Table 1 classifies all plastics under a single category, it is important to understand not all plastic is the same, especially with respect to behavior as an asphalt binder modifier. Table 2 further delineates common types of plastics based on the familiar Resin Identification Codes (RICs). As will be discussed in more detail throughout this E-Circular, plastic types vary in their readiness to serve as a binder modifier, based on properties such as melting points, molecular weights, and solubility parameters. Compatibility between plastic and asphalt binder will be a

TABLE 1 General Classification of Asphalt Additives (4–6)

Group	Category	Description
1	Mineral fillers	Dust, lime, portland cement, carbon black, fly ash
2	Extenders	Sulfur, lignin
3	Rubbers	Natural latex, synthetic latex (SB), block copolymer (SBS), reclaimed rubber (crumb rubber)
4	Plastics	Polyethylene [PE, low-density polyethylene (LDPE), HDPE, linear low-density polyethylene (LLDPE)], polypropylene (PP), ethylene-vinyl-acetate (EVA), polyvinyl chloride (PVC, note that this is hazardous in asphalt due to chlorinated gases generated)
5	Combinations	Combinations of polymers in Groups 2, 3, or 4
6	Fibers	Rock wool, polypropylene, polyester, fiberglass
7	Oxidants	Manganese, other mineral salts
8	Antioxidants	Carbon, calcium salts
9	Hydrocarbons	Recycling oils, rejuvenating oils
10	Antistrips	Amines, lime
11	Waste Materials	Roofing shingles, recycled tires, glass

TABLE 2 ASTM D7611 RICs and Examples

Code	Category	General Uses
1	Polyethylene Terephthalate (PET)	Water and drink bottles, food packaging and containers, medicine containers
2	High-Density Polyethylene (HDPE)	Flexible pipes, plastic toys, shampoo and conditioner bottles, juice and milk jugs, cleaning supply containers, 5 gal buckets
3	Polyvinyl Chloride (PVC)	Pipes, cable sheathing, pool liners, vinyl flooring, sign boards
4	Low-Density Polyethylene (LDPE)	Plastic wraps, plastic bags (trash bags, sandwich bags, bread bags, produce bags)
5	Polypropylene (PP)	Carpet fiber, plastic chairs, reusable plastic containers (e.g., yogurt and sour cream), plastic caps
6	Polystyrene (PS)	To-go containers, disposable flatware, CD and DVD cases, foam beverage cups, disposable razors
7	Other (Polycarbonate, PC; Acrylonitrile Butadiene Styrene, ABS; Nylon; Fiberglass; Acrylic)	Baby bottles, water coolers, safety glasses, car parts

prevailing theme throughout this E-Circular as it is one of the more prominent challenges to modification with plastics, though there are other factors that require careful research as well.

The desire to use plastics as modifiers is, more specifically, coupled with the desire to recycle waste plastics (particularly post-consumer recycled plastics). This adds further logistical challenges since post-consumer waste streams generally contain mixed and contaminated plastics. Some level of sorting and cleaning would likely be required, which in turn has economic implications. These factors can be overcome, but they represent a piece of the larger puzzle which must also be addressed to achieve the goal of responsible recycling.

SUMMARY

Efforts to better understand how to produce, collect, recycle, and engineer plastics for use in asphalt pavements are ongoing, and this E-Circular is simply one resource of many. Recently, the National Academies of Sciences, Engineering, and Medicine published a consensus study report that considers recycled plastics within the context of all infrastructure (9). It represents a growing body of literature and knowledge within the civil engineering community at large. While the challenge of managing waste plastics is increasingly being viewed as one that cuts across numerous aspects of infrastructure and society, information presented throughout the remainder of this E-Circular focuses specifically on applications within asphalt pavements.

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Use of Plastic in Asphalt Mixtures and Pavements

History and Future Challenges

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Plastics are ubiquitous as they are any of numerous organic, synthetic, or processed materials that are mostly thermoplastic or thermosetting polymers of high molecular weight that can be made into objects, films, or filaments. They are more commonly derived from petrochemicals, although some variants are made from renewable materials. Usually low-cost and easy to manufacture, they can be used in a multitude of products from paper clips to spacecraft. This has made them prevalent in the last century over traditional materials such as wood, stone, horn, bone, leather, metal, glass, and ceramic. Their general chemical stability or inertia make them generate considerable amounts of waste, environmental, or even health hazards, such as microplastics or plastic islands like the Great Pacific Garbage Patch in the Pacific Ocean, to name a few.

This paper focuses on the potential to use plastics in asphalt and the hurdles or questions that need to be addressed for an appropriate and responsible usage that benefits all stakeholders. It focuses on some issues and suggests some guidelines so that performance, recyclability, environmental friendliness, and cost effectiveness of flexible pavements should not be sacrificed by wrong or incorrect usage of plastic wastes.

INTRODUCTION

Plastics are ubiquitous as they are any of numerous organic, synthetic, or processed materials that are mostly thermoplastic or thermosetting polymers of high molecular weight that can be made into objects, films, or filaments (1). They are more commonly derived from petrochemicals, although some variants are made from renewable materials. Usually low-cost and easy to manufacture, they can be used in a multitude of products from paper clips to spacecraft. This has made them prevalent over traditional materials such as wood, stone, horn, bone, leather, metal, glass, and ceramic. Their general chemical stability or inertia make them generate considerable amounts of waste, environmental, or even health hazards, such as microplastics or plastic islands like the Great Pacific Garbage Patch in the Pacific Ocean, to name a few. This paper focuses on the potential to use plastics in asphalt and the hurdles or questions that need to be addressed for appropriate and responsible usage that benefits all stakeholders.

Worldwide production of all plastics was reported to be approximately 300 million tons annually in 2019 (1). The most common is polyethylene (PE), primarily used in packaging such as plastic bags, plastic films, geomembranes, and containers, e.g., bottles (mostly disposable products). To achieve the appropriate application characteristics, numerous kinds are produced industrially: low-density (LDPE), high-density (HDPE), linear low-density (LLDPE), as well as copolymers of PE with other synthetic polymers. As a result, over 110 million tons of polyethylene resins are produced annually, representing about 37% of the total plastics market.

The industry has gotten to this level of production over the span of a century, starting prior to the 20th century, which is considered as the “golden age” of plastics (2). A brief historical perspective (3):

- 1898: Pechmann first synthesized PE—it was accidental, not industrially practical.
- 1933: Fawcett–Gibson [Imperial Chemical Industries (ICI)] synthesized first industrially practical PE, low-density (LDPE)—again, accidental.
- 1935: Perrin, high pressure synthesis of LDPE:
 - 1939: Industrial production began and
 - 1944: Commercialization carried out under World War II-related secrecy for coaxial insulation.
- 1951: Banks–Hogan (ICI), CrO_3 catalyst breakthrough allowing commercial polymerization at mild temps.
- 1957: Montedison, first commercial production of crystalline polypropylene (PP).
- 1963: Nobel Laureates Ziegler–Natta (ZN Catalyst):
 - 1953: Carl Ziegler, synthesis of higher density olefins (HDPE) (Z Catalyst – TiCl_4 supported) and
 - 1954: Giulio Natta, synthesis of crystalline PP, (N Catalyst).
- Third generation catalyst breakthrough (MgCl_2 supported).
- 1976: Kaminsky–Sinn, metallocene catalysts.
- ZN catalysts and metallocenes flexible at copolymerizing ethylene and other olefins available today.
- PE is most common plastic.

Focusing on applications, below is an overview on plastics typically used in asphalt binders and asphalt mixtures (4, 5):

- The application of atactic polypropylene (APP) was originally developed by Romolo Gorgati in 1964 and is still very much used for roofing asphalt systems. This is a good example of successful use of waste plastics in modified asphalt binders. The process of modifying asphalt binder with APP was, in fact, so successful that the stockpile of waste APP was depleted. This, combined with the fact that new processes for production of PP did not yield waste APP, made it necessary to custom produce APP for roofing asphalt binder modification.
- Copolymers of ethylene and other monomer types are used as plastomers, some featuring limited elastomer characteristics, for asphalt paving applications such as EVA (examples of suppliers and brands include ExxonMobil Polybilt and SK Functional Polymers Evatane), or ethylene butyl acrylate (EBA) (e.g., ExxonMobile EnBA, SK

Functional Polymers Lotryl), or ethylene-methyl acrylate-glycidyl methacrylate (terpolymers) (e.g., Dow ELVALOY and SK Functional Polymers Lotader). Oxidized PE (e.g., Honeywell Titan) is also used.

- Amorphous poly-alpha-olefins (APAO) (e.g., Evonik Industries Vestoplast), amorphous polyolefin (APO) (e.g., Westlake Chemical EE-2), and thermoplastic polyolefin (TPO) such as ethylene-propylene-butene (e.g., LyondellBasell Catalloy) are used for special applications.
- LDPE was used to a high extent in the 1990s through a special process involving continuous stirring (Feldsinger Construction, Novophalt) to prevent phase separation.
- Many of these plastics have been used under the wet process through a direct addition and mixing with a base asphalt binder. This includes use of LDPE: Novophalt in Austria, as mentioned; polyolefins such as APP in Italy, sometimes in the presence of polyphosphoric acid (PPA); and PE/PP blends in the presence of tall oil in Finland.

This list shows examples that the asphalt industry has considerable experience using plastics or plastomers in asphalt binders. Plastic waste recycling in asphalt, however, goes back to 1970s–1990s particularly in Europe, principally using the dry process, where waste plastics are directly added to the asphalt–aggregate mixture in the plant. Telephone cable wastes (LDPE granules) were used in France for reinforcing mixes with some fair success. HDPE waste was used in Gussasphalt (mastic asphalt) in Germany but had increased brittleness and contraction (5).

A recent National Center for Asphalt Technology–National Asphalt Pavements Association (NCAT–NAPA) publication presents an updated and more complete survey of the application of plastic and plastic wastes in asphalt binder and asphalt mixture, including a literature review and state of the knowledge (6, 7).

CONSIDERATIONS

Several considerations might be listed to help avoid potential early failures and reach appropriate performance, defined as performance as good as or better than current practice.

These considerations include:

- Will the desired performance characteristics be achieved?
- Will specifications be met consistently?
- Are there testing considerations?
- What are the handling and incorporation issues?
- Will it be storage and service stable?
- Will it be heat stable?
- Are there constructability issues?
- Will it be (re)recyclable?
- Are there health, safety, and environmental (HS&E) considerations?
- Are costs reasonable?

From this point, this paper presents a review of each of these considerations to aid the industry moving forward in avoiding obvious pitfalls.

Performance Characteristics and Specifications

The Superpave binder specification system in use in North America and some other parts of the world is primarily based on the measurement of binder stiffness as a function of temperature. Figures 1 and 2 schematically present the Superpave grading system in general and for a few Performance Grading (PG) grades. Better grades usually feature wider useful temperature intervals (UTIs), represented as the difference between the upper and lower continuous temperature limits and lower slopes, indicating lower temperature sensitivity. Similar representation can be made using classical empirical specification systems from viscosity or penetration as a function of temperature.

When adding plastic such as polyethylene to a virgin neat asphalt, the main noticeable effect is stiffening. Rahman et al. (8) presented a study showing that the stiffening effect was quasi linear as a function of PE content, as measured by penetration decrease and ring and ball (R&B) softening point increase, as shown in Table 1 and Figure 3 excerpted from Rahman et al. (8).

Such a linear effect is not common for asphalt polymer modification where it is known that stiffening usually increases up to an asymptote at a critical polymer content that leads to a phase inversion, where the polymer becomes the continuous phase, as shown in Figure 4 for EVA (5). This observation shows that the modification mechanisms for EVA and PE are different, which will be discussed later.

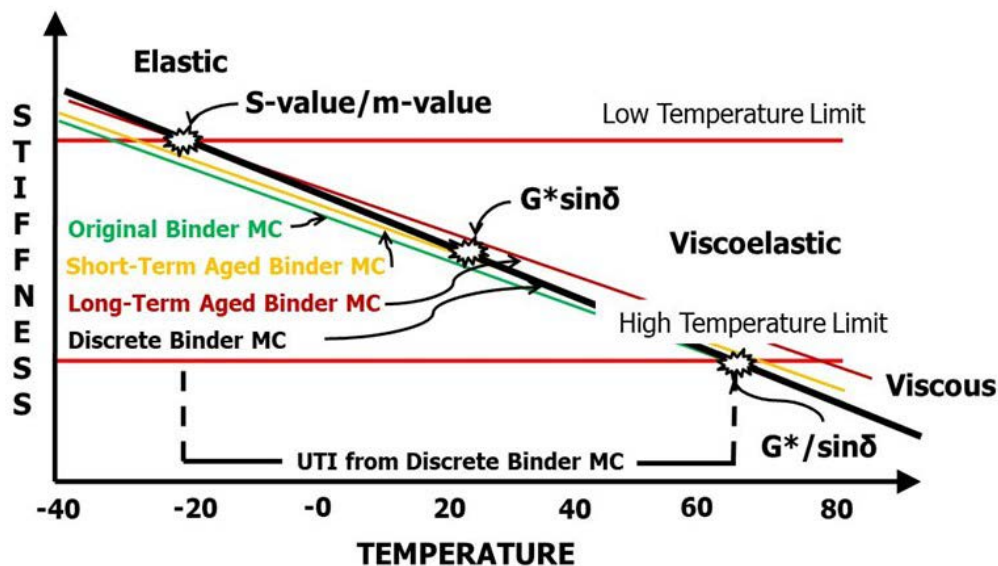


FIGURE 1 Superpave binder specifications: asphalt stiffness and performance limits as a function of temperature (°C) and UTI.

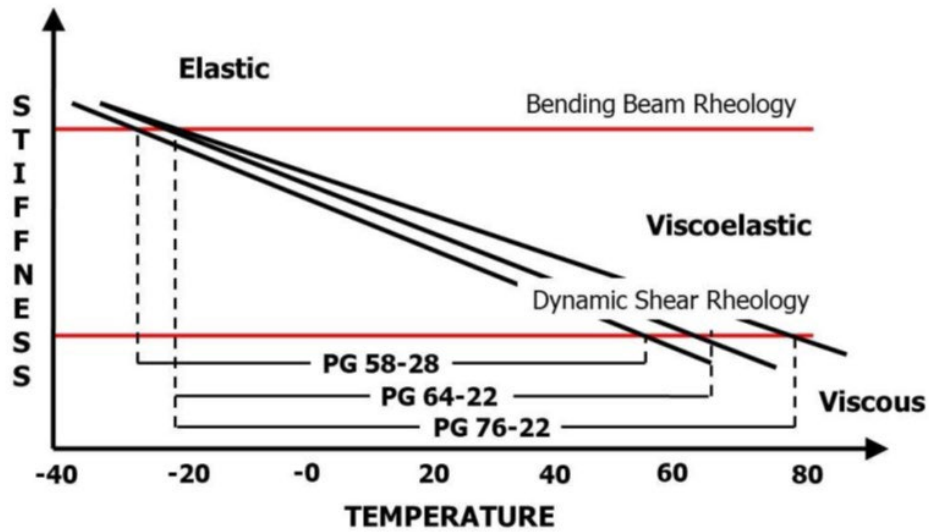


FIGURE 2 Superpave binder specifications: PG UTI as a function of temperature.

TABLE 1 Properties of Asphalt Binder Modified with Polyethylene (8)

Properties	Percentage of Polyethylene							
	2.5	5	7.5	10	12.5	15	17.5	20
Penetration (dmm)	76	71	66	59	53	49	45	39
Ductility (cm)	85	77	67	55	49	42	38	34
Solubility (%)	95.44	89.25	85.2	82.8	79.55	76.98	73.13	69.91
Flash Point (°C)	280	265	240	230	210	190	175	165
Fire Point (°C)	290	275	250	240	220	200	185	175
Specific Gravity	1.0145	1.0085	1.004	0.998	0.995	0.992	0.987	0.985
Softening Point (°C)	55	59	61	66	71	78	81	83

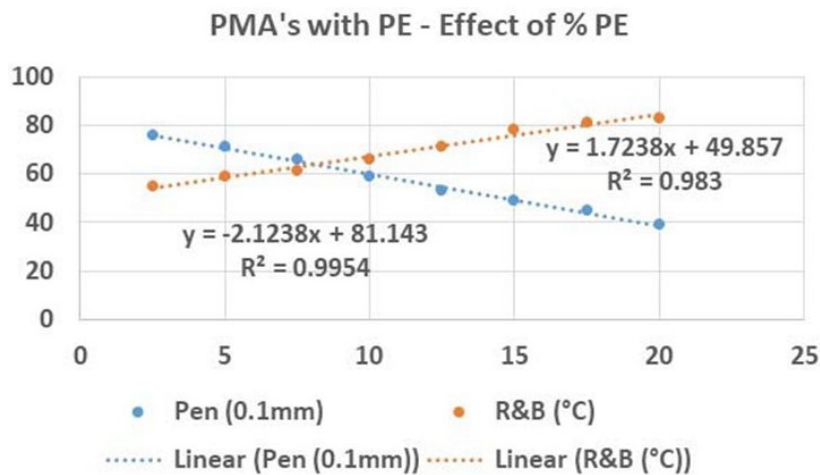


FIGURE 3 Penetration and softening point as a function of PE content (from Table 1).

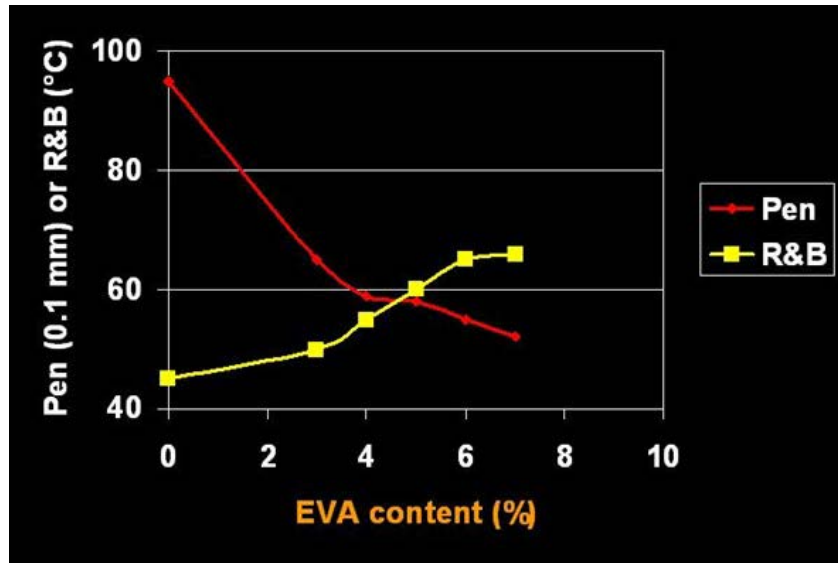


FIGURE 4 Penetration and softening point as a function of EVA content.

In terms of Superpave specifications, addition of PE (LDPE) increases both the upper and lower PG temperatures, again showing a stiffening effect as seen in Figure 5 (9). The effect is somewhat similar for EVA but significantly different for SBS elastomers either chemically cross-linked or which do not stiffen the low temperature end.

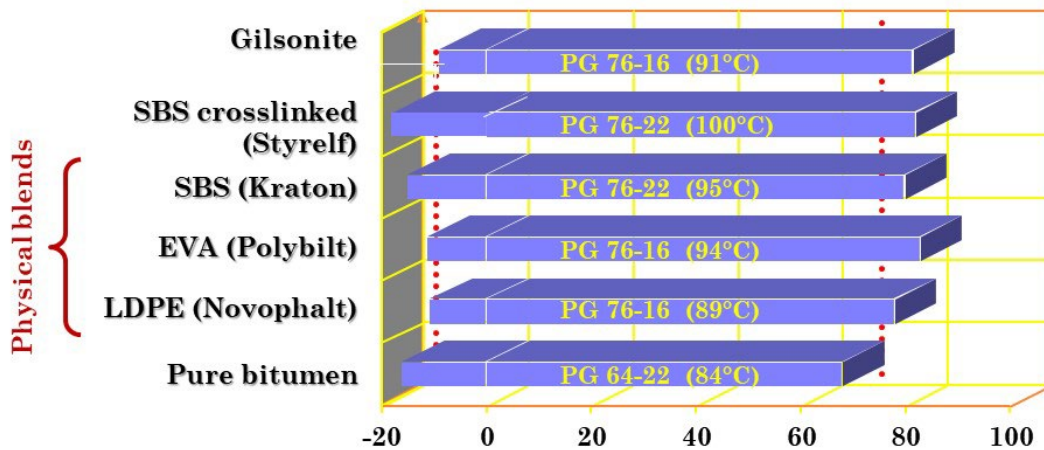


FIGURE 5 PG extracted binders after 7 years in service on I-80, Pennsylvania (9).

TESTING CONSIDERATIONS

Crystallinity

Crystallinity is the nature of plastics and can play a role in terms of thermal history sensitivity that may develop hysteresis that can impact rheological measurement. The stiffness at a given temperature may be different whether the plastic-modified binder sample was assessed upon heating or cooling, as well as the cooling or heating conditions. This can affect bending beam rheometer (BBR), dynamic shear rheometer (DSR), and multiple stress creep and recovery (MSCR) measurements.

Time Dependent Hardening (Low Temperature) or Softening (High Temperature)

Since crystallization is kinetics-related and since plastics are high molecular weight molecules, they take time to reach equilibrium state. This can lead to time dependent physical hardening or softening depending on the temperature testing regime.

Differential Thermal Expansion/Contraction

Thermal expansion and contraction properties can be different for plastics compared to asphalt binders or asphalt mixtures. Resulting differential movement can initiate micro cracks, which can turn into macro cracks detrimental to thermal or load-related fatigue cracking resistance.

Inhomogeneity

Since the blends are usually inhomogeneous, sample representability can become questionable. Polymers of different polarity tend to self-assemble or agglomerate with their own kind, rejecting other kinds, to form separate phases. Many compounds in asphalt binder are polar and, like polymers, self-assemble forming multimolecular clusters within the asphalt binder. Blending polymers and asphalt binder of disparate polarities may enhance phase separation and incompatibility. Validity of current test methods such as storage stability, e.g., R&B softening point, may not extend to all types of asphalt binder-polymer blends.

Bitumen–Polymer Compatibility and Stability

Compatibility

When blending any bitumen with any polymer, there are three possible scenarios (5):

- Completely heterogeneous blend. Case of a truly incompatible polymer and bitumen.
- Completely homogeneous blend. Case of the complete dissolution of the polymer in the bitumen. This case of ideal compatibility leads to a huge viscosity build-up at handling temperatures and not necessarily appropriate properties at service temperatures.
- Swelling of the polymer. This is generally the appropriate compatibility of a polymer with a bitumen that leads to improved characteristics at service temperatures. The resulting polymer-modified asphalt (PMA) is a biphasic system at some level – micron level in general. This is classically observed using fluorescence microscopy where swollen

polymer nodules appear circular (lower energy state) and fluorescent as in Figure 6. Note that neither the asphalt nor the polymer fluorescence alone. The molecules that fluoresce are polycondensed aromatics present in asphalt, for which fluorescence is normally naturally quenched by the presence of asphaltenes. The fluorescence is revealed when these aromatics are separated from asphaltenes through their swelling of the polymer due to their chemical affinity with the polymer (5).

In some respects, successful blending of bitumen and polymer is a matter of thermodynamics matching (5, 11). The chemical affinity or compatibility of a bitumen with polymer is a function of its asphaltene and maltene molecular structures, as well as the presence of waxes, metal, salts, and so forth. The compatibility of a polymer with asphalt binder is function of the polymer's chemical composition and molecular weight. Blend compatibility is a function of all the above, the blend composition, and the solubility parameters of the components (square root of the cohesive energy density). As a result, maltenes and polymer solubility parameters need to match as close as possible.

Figures 7 and 8 illustrate the thermodynamics match in equations and the importance of molecular weight. The equations in Figure 7 address the thermodynamics of the mixing of a polymer (P) in a bitumen (B). The first equation describes the Gibb's free energy (ΔG_{mix}) which has to be negative for the mixing to be thermodynamically feasible; ΔH_{mix} , and ΔS_{mix} are the the enthalpy and entropy of mixing at temperature (T). The second equation is based on Flory-Huggins equation and accounts for the volume fraction (Φ) of the components of the mix (bitumen B and polymer P). The mixing or interaction parameter (χ) considers the energy of dispersing the polymer and bitumen molecules. The third equation enables the interaction

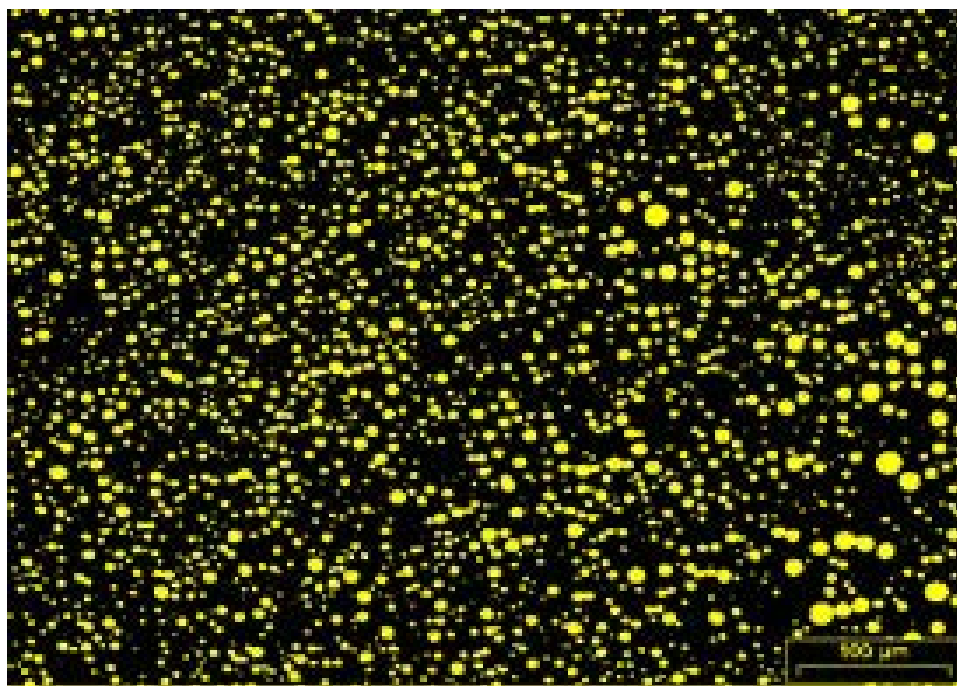
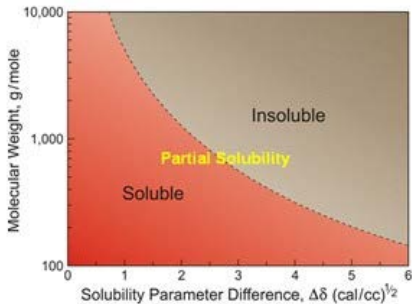


FIGURE 6 Fluorescence microscopy of SBS-modified asphalt, 100-micron scale.

- ❖ $\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix}$
- ❖ $\Delta G_{mix}/RT = (\phi_B/\chi_B)\ln\phi_B + (\phi_P/\chi_P)\ln\phi_P + \chi_{BP}\phi_B\phi_P$
- ❖ $\chi_{BP} = (\delta_B - \delta_P)^2/RT$



Famous names in this area

- Hildebrand - Scatchard
- Hansen
- Van Krevelen
- Flory-Huggins...

FIGURE 7 Thermodynamics equations introducing solubility parameters (δ) for a given polymer (p) bitumen (b) blend, and effect of molecular weight (δ).

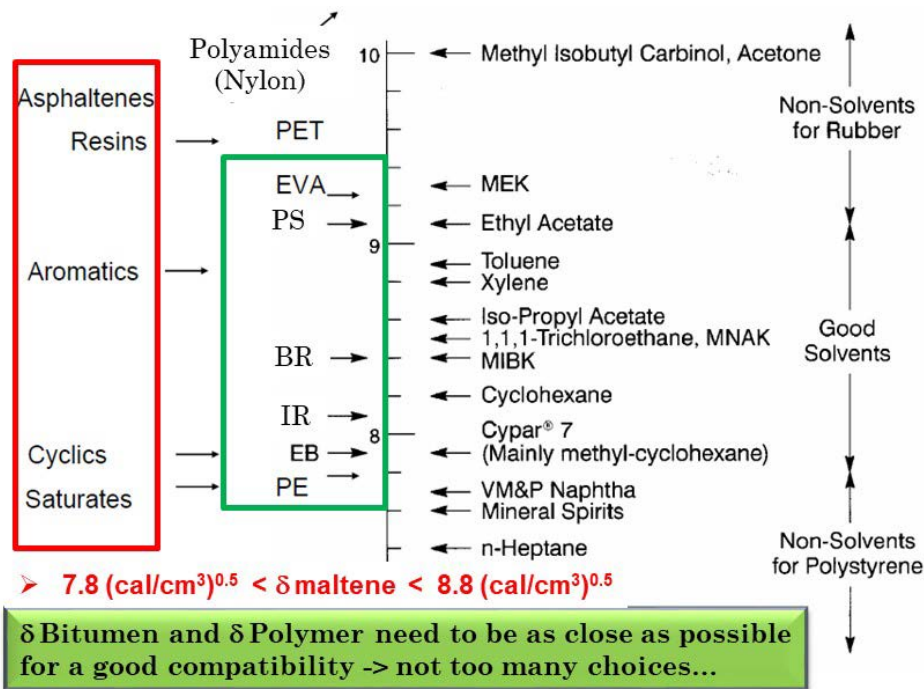


FIGURE 8 Solubility parameters scale for polymers, asphalt fractions, and solvents (5).

parameter (desirable to be as small as possible) to be estimated from the Hildebrand solubility parameters of the bitumen δ_B and the polymer δ_P .

Ultimately, Figures 7 and 8 illustrate that most polymers are incompatible with asphalt fractions. For example, polyethylene terephthalate (PET) may be compatible with asphaltenes and resins but not with aromatics and saturates, while PE is just the opposite, compatible with saturates only. SBS is in between the solubility of polystyrene (PS) and butadiene rubber and at a middle point.

The effect of polymer molecular weight is significant—the higher the molecular weight, the closer the solubility parameter of the solvent (asphalt binder in case of PMA) needs to be to the polymer. This explains solubility issues between high molecular weight HDPE and asphalt binder for example. On the other hand, a classical SBS 30%/70% styrene-butadiene content with an average molecular weight around 200,000 Daltons, a narrow molecular weight distribution range (1.1–1.3), and a solubility parameter of around 8.5 would fit within the solubility/molecular weight range for an appropriate compatibility (appropriate swelling) (10).

Storage Stability

One of the properties most affected by polymer compatibility in asphalt is storage stability. This paper focuses on three key factors related to it:

- Morphology of plastic/bitumen blends (5, 11),
- Stokes law, and
- Testing challenges.

At service temperatures, PMAs are generally biphasic materials with micro-heterogeneities, with a polymer phase solvated by a part of the maltenes and a bitumen phase including constituents not involved in the polymer solvation process. The polymer swelling rate can go up to 1000% volume for SBS—the polymer phase enriched in lighter maltene molecules then features a lower density. On the other hand, the bitumen phase becomes enriched in asphaltenes which are not compatible with the polymer, particularly in case of polyolefin plastics. As a result, the bitumen phase density becomes higher. A competition between asphaltenes and polymer takes place to “attract aromatics” necessary to ensure their solvation. This competition eventually leads to instability.

The swelling rate decreases with the polymer content, as the “good swelling” aromatics are in limited amount. The phase system evolves as well from a bitumen continuous phase at low polymer content to a polymer continuous phase at high polymer content. The transition with co-continuous phase at intermediate polymer contents is where major changes in properties occur, such as an increase in softening point, or stiffness modulus, as presented in Figure 3 for EVA PMAs. Figure 9 shows ultraviolet (UV) microscopy images at three SBS concentration. Note that at high temperature (i.e., at or above process temperature), PMAs are usually monophasic and become multiphase upon cooling.

Storage stability at high temperature is then very much regulated by physical parameters and Stokes law on sedimentation under the force of gravity of small particles in a fluid (13). Figure 10 details interactions between PMA microstructure, Stokes law, and storage stability.

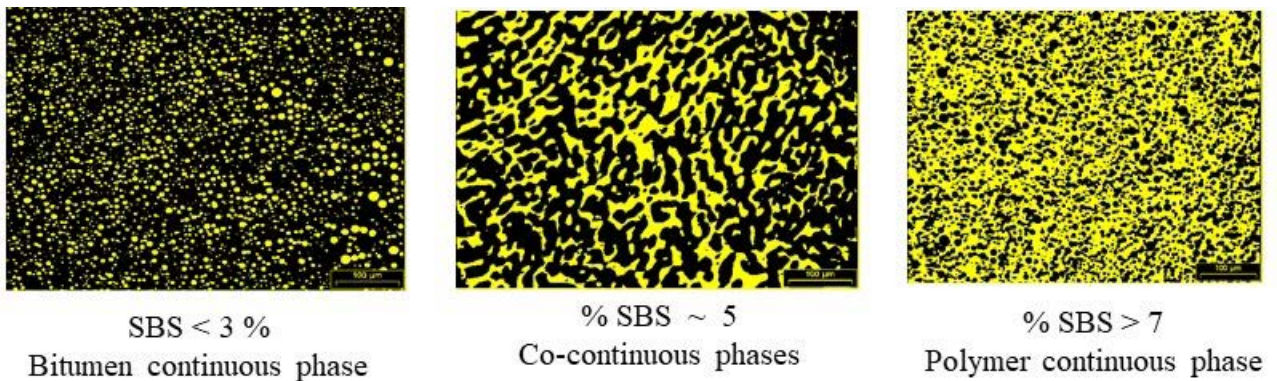
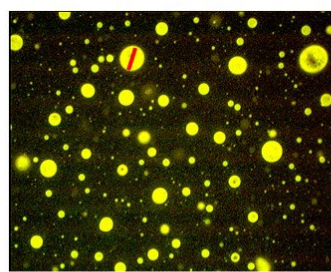


FIGURE 9 Changes in PMA microstructure as a function of polymer content (5).



○ Sedimentation, under the force of gravity, of small particles, in a fluid

- Settling velocity of droplets
 $dx/dt = 2r^2(\rho_2 - \rho_1)g/9\eta$
- r = radius of the droplets
- ρ_1 = density of the external fluid
- ρ_2 = density of the droplets
- η = viscosity of the matrix

Assuming PMA as swollen polymer droplets in an enriched asphaltene matrix, Stokes' law tells:

- > Creaming if $\rho_2 < \rho_1$ → polymer phase
- > Settling if $\rho_2 > \rho_1$ → asphaltene phase
- > Can be cancelled out by the matrix viscosity (PMA concentrates)

FIGURE 10 Stokes Law and PMA microstructure to explain storage stability.

Other parameters play a role in storage stability kinetics such as:

- Storage temperature and time;
- Polymer content—viscosity;
- Phase density difference;
- Polymer swelling, solubility, microstructure; and
- Tank geometry, size, and agitation.

Getting these parameters under control can make huge differences, as presented in Figure 11 for a plant storage case where tank layers were analyzed against polymer-rich and asphaltene-rich phases as a function of storage time at 180°C for a plastomer PMA in a vertical storage tank in absence of agitation (5).

Another challenge with storage stability is the relevance of the testing protocol. Regardless of the specification, the storage stability testing protocol involves filling and storing a cigar tube vertically at 163°C for 48 h (temperature and time may differ depending on the specification) with no agitation and no/little convection as illustrated in Figure 12. The assessment always

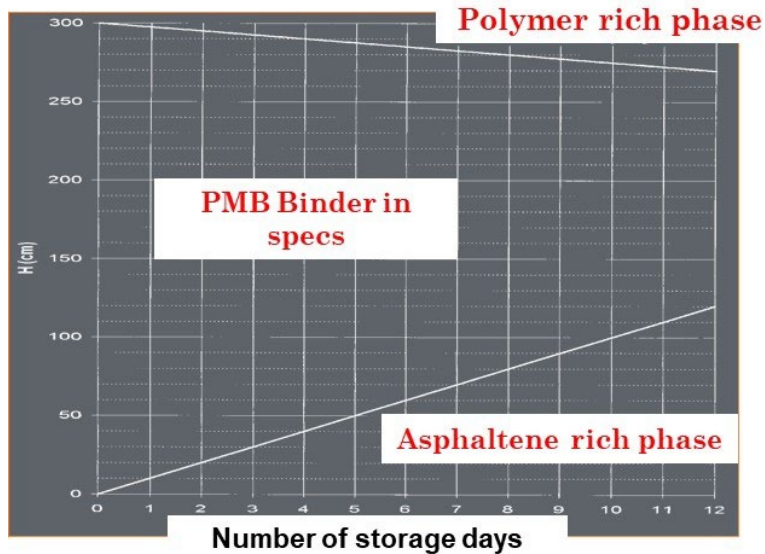


FIGURE 11 Storage stability in a vertical tank—Plastomer PMA (5).

involves the comparison of the top and bottom 1/3 portions. However, what property is assessed makes a difference:

- R&B softening point, as in ASTM D7173 (14), is essentially a viscosity and is similarly affected by asphaltenes and polymers. No change in R&B softening point does not mean no phase separation because viscosity increases with both polymer and asphaltene content. $G^*/\sin \delta$ would react similarly to this asphaltene/polymer dilemma.
- Penetration at 25°C is more discriminant because it differentiates the hard asphaltene-rich phase with low pen from the soft polymer-rich phase (swollen by lighter maltenes) with high pen. In the case of SBS or EVA separation, the polymer phase creams (goes to the top), and the asphaltene phase settles down (goes to the bottom). This can be different for other polymer systems.
- MSCR %Recovery is also very sensitive to composition and differentiates asphaltenes (low recovery) from polymers (high recovery).

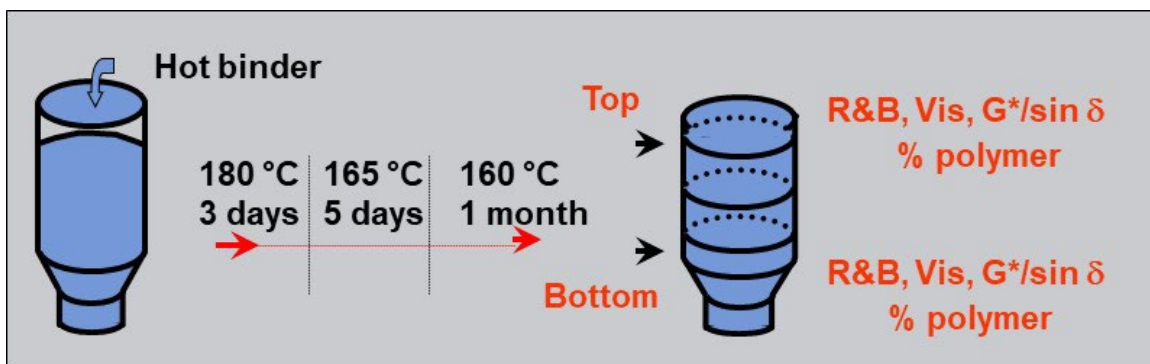


FIGURE 12 Example of storage stability test conditions and assessment.

How does this all apply to plastic-modified asphalt? The following is part of a study carried out at NCAT with the participation of the Western Research Institute (WRI) and a funding from the plastic industry association (15).

Various blends of bitumen with recycled polyethylene plastics (RPE) and reactive ethylene terpolymer (RET) (DuPont) were prepared as presented in Table 2 and assessed in terms of storage stability according to Georgia Department of transportation (DOT) specification based on R&B softening point. The table shows that blends with up to 3% RPE were storage stable and could be further slightly improved with RET addition. Blends with 5% RPE were very instable and could not be improved. Blends with 4% RPE were slightly instable and could be improved with RET addition to pass the Georgia DOT specification.

However, the Georgia DOT specification is Δ R&B softening point $<10^{\circ}\text{C}$, whereas EN14023 specification (used in Europe for PMAs) is Δ R&B softening point $<5^{\circ}\text{C}$ with Δ Penetration limits of 9 to 26 depending on the specification class. According to EN 14023, the 4%RPE+RET2 blend in Table 2 would fail when it passed under the Georgia DOT specification.

Under the UV fluorescence microscope, most blends would show heterogeneous microstructures, somehow like Figure 13. However, this 5% RPE blend was the most heterogeneous. It does not show the same swelling “regular/circular” pattern as classical SBS (see Figure 5). Further study is needed to understand why – likely related to a different swelling mechanism.

WRI went further in terms of assessing blends by carrying out MSCR at 58°C on top and bottom thirds of stored samples. Figure 14 compares the nonrecoverable compliance J_{nr} and the % recovery for the top and bottom samples for four of the blends. The neat and RET blends were perfectly stable as expected, but the 3% RPE with and without RET showed significant instability. The RET addition did reduce the instability but not completely. Note that the instability was also confirmed by chemical analysis (SAR-AD) of unstirred/stirred samples and by UV microscopy. These results are not presented in this paper, but more information on this type of approach, developed at WRI, can be found elsewhere in detail (16, 17). Under GDOT specification, both 3% RPE binders passed the stability test. This confirms the original assumptions on the importance of testing validity. R&B softening point is not discriminant enough for plastic-modified binders. Meanwhile, RET additive does improve the situation, and one can conclude that the quest for compatibilizers is tough but open and relevant.

TABLE 2 NCAT RPE Blends Storage Stability Assessment According to Georgia DOT Specification

Binder ID	R&B Softening Point ($^{\circ}\text{C}$)			Pass/Fail GDOT Requirement
	Top	Bottom	Difference	
2% RPE	46	43	3	Pass
3% RPE	47	44	3	Pass
4% RPE	60	45	15	Fail
5% RPE	80+ *	48	32+	Fail
3% RPE + RET1	54	52	2	Pass
4% RPE + RET1	80+ *	48	32+	Fail
3% RPE + RET2	54	52	2	Pass
4% RPE + RET2	57	48	9	Pass
5% RPE + RET2	80+ *	52	28+	Fail

Note: * Exceeds the upper temperature range of the ASTM low softening point thermometer

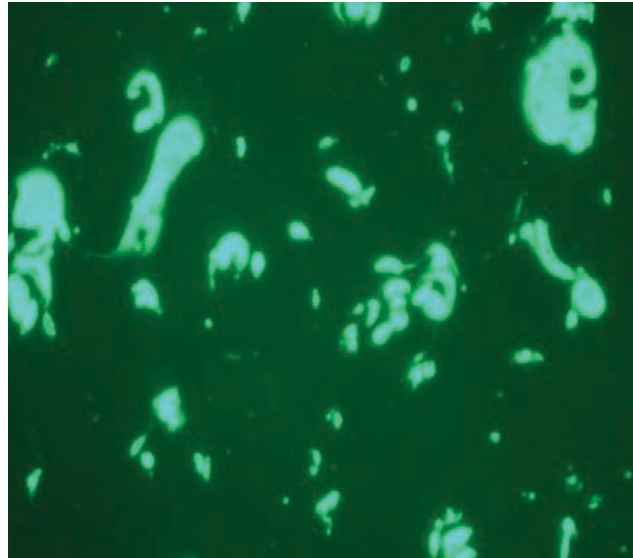


FIGURE 13 Fluorescence micrograph of 5% RPE-modified binder without RET additives.

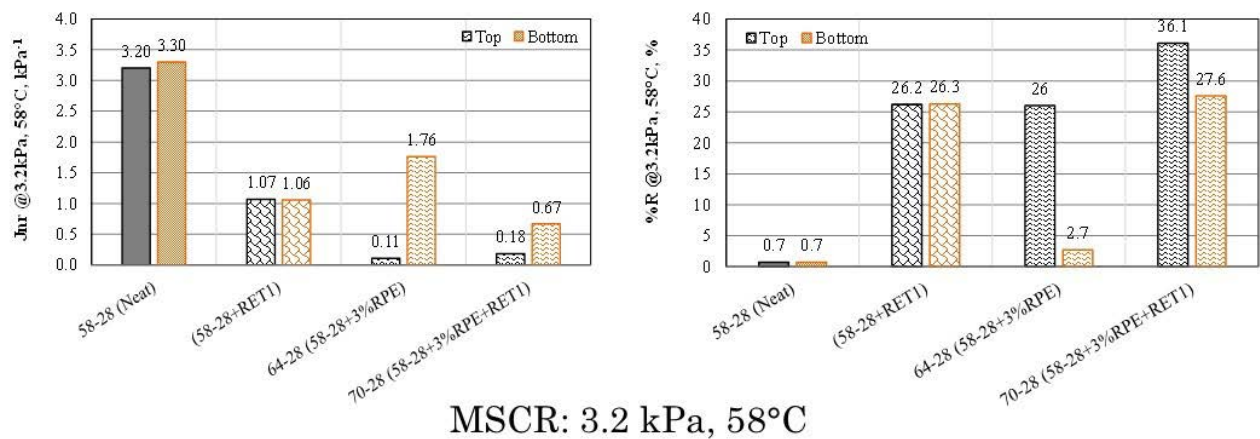


FIGURE 14 NCAT–WRI storage stability study based on MSCR.

Handling, Incorporation, Construction

At the production process level, plastics will be stored, conveyed, and handled as solid. At this stage, the main risk would be the presence of fine powder that could generate flammability. When mixed at high temperature, either in the asphalt liquid in case of wet process or in the asphalt–aggregate mix in case of dry process, odors may be of concern. The type of low/higher shear mixer may come into play for the wet process depending on the type of plastics and, particularly, its melting point. Storage agitation is likely to be challenging and recommended.

Temperature control with respect to the melting point is going to be key at various stages of production and construction. Construction issues are likely to be related to waste plastic melting point (MP) as it depends on a plastic’s nature and molecular weight and it imparts such a drastic

change in viscosity. More specifically, MP will impact handling (e.g., pumping), mixture workability, and compaction; all are nonissues above the MP but difficult below.

Re-Recyclability

Because asphalt is the most recycled material in the world, it is of the utmost importance that any modification system will not deteriorate this attribute. This therefore raises a few questions regarding:

- The performance of reclaimed asphalt pavement (RAP) blends or mixes including plastics: will they impart special performance or request special attention?
- Construction of pavements with RAP blends or mixes including plastics: can they be handled just like any RAP, or if not, should they be segregated? Unknowns are likely related to MP and plastic nature.
- Uniformity of RAP containing plastics: will plastics present segregation issues?
- If RAP containing plastics cannot be handled or utilized similarly to any other RAP, will additional identification and handling be required? This would add another layer of testing and therefore complexity.
- Others?

Health, Safety, and Environment

Even though most plastics are rather chemically stable, which leads to one of their most prominent environmental issues of not being biodegradable, a few health, safety, and environmental (HSE) related items need more in-depth research, information, and dissemination to users.

- Though generally chemically stable, under elevated temperature conditions possible risks include odor and corrosion, depending on the plastic waste.
- Can fumes be generated under high-temperature processing of plastic wastes? This is certainly a function of process temperature, but even more of plastic waste nature. EVA is known to release acetic acid (vinegar smell) at temperatures above 300°C. Polyvinyl chloride (PVC) is likely to release hydrochloric acid and dioxin upon burning or under certain high-temperature conditions; this can also lead to corrosion of steel equipment (e.g., pipes, tanks, pumps) (18). Plastic wastes may also require neutralization of the flue gas, or other gaseous emissions. High volume plastics such as polyolefins like PE or PP are rather stable though against thermal degradation.
- Impact on International Agency for Research on Cancer (IARC) classifications (paving/roofing): will plastic addition affect IARC classification on paving and roofing asphalt fumes?
- Leaching is not probable due to hydrophobicity of most plastics, but what about plastic additives, such as extenders or plasticizers?
- Micro plastics generation is a new HSE topic that certainly needs consideration. Can plastic-modified asphalt generate micro plastics particles as a result of traffic wear and abrasion?

- Are there any further items to consider?

Costs and Economics

Although cost discussion is not the purpose of this paper, general considerations can be presented. Several factors are likely to impact cost:

- Recycled plastic sorting: is a waste still a waste when it has to be sorted? The issue with plastics is that they are diverse and not just plastics, as described in this paper. If the recycling process can accommodate high MP or acid releasing plastics, then some sorting will be needed.
- Recycled plastic logistics: storing, conditioning, and shipping will add cost, similarly to any polymer or additive.
- Is plastic treatment needed?
- Grinding may be needed depending on the plastic waste shape to ease the incorporation of the plastic, either in the hot mixing system in a hot mix asphalt (HMA) plant in the case of the dry process or in a liquid binder tank in the case of the wet process. These two processes will differ in their prerequisites to accommodate plastic incorporation.
- Binder formulation: the wet process could require the use of a processing or compatibility aid (additive).
- Storage cost: as the plastic waste-asphalt binder blends are likely incompatible, agitation will be mandatory to avoid phase separation in storage tanks.
- Extrusion/pyrolysis: special processes may be requested for certain processes or applications. This would be an upstream cost that could be passed onto the end-user to some extent and certainly should be considered for further life cycle cost analysis.
- Other costs may also need to be considered.

SUMMARY

One of the most important takeaways from this paper is that plastics are not simply plastics; they can be very different materials in nature and properties, even more so when it comes to plastic wastes. In many instances they may require some sorting that will add significant cost.

Plastics are generally incompatible with asphalts, leading to storage instability and possible cracking potential. This is primarily related to their polyolefin composition which imparts solubility parameters too different from that of asphalt maltene and asphaltene fractions, but then amplified by their high molecular weight.

Plastics are crystalline in nature with high molecular weights and sharp MPs generally well above 100°C. This crystallinity dictates their properties and their asphalt stiffening effect at temperatures below their MP.

This stiffening effect is expected to be good for rutting resistance but likely detrimental for cracking resistance. It is important to understand how plastics' crystallinity can impact low-temperature internal restraint mechanisms, which is likely to impact asphalt's typical thermal contraction (19). This may have an impact one way or another on block cracking potential

according to a recent study (19). Assessing these plastic-modified asphalt blends will also require looking at failure properties in addition to rheological ones (20).

Their crystallinity makes plastic and asphalt blends sensitive to thermal history, which needs to be considered for specification testing that could be flawed by hysteresis issues upon cooling vs. heating, for example, and may require more clearly defined testing procedures.

Plastics are easy to handle while solid at ambient temperature and are very fluid above MP. However, their viscosity drastically increases below melting, and therefore, plastic-modified asphalt mixture compaction temperature may need special attention depending on the plastic melting point.

Even if much is already known, many unknowns remain. There is a need for more research particularly to cost effectively improve compatibility and adequately characterize the materials during their whole service life and regarding their recyclability. Potential environmental issues may also need attention such as possible micro-plastic generation under traffic wear.

National projects are currently ongoing in the United States on the topic of recycling plastics in asphalt related applications:

1. NCHRP 9-66 project related to the mixes obtained through dry process, entitled “Mechanical Properties of Laboratory Produced Recycled Plastic-Modified (RPM) Asphalt Binders and Mixtures”. Projected completion date is August 30, 2024. More information on this project can be found at: <https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4961>
2. FHWA Exploratory Advanced Research study related to the wet process entitled “Improving the Compatibility of Waste Plastic and Asphalt Binder via Theoretically Justified Identification of Compatible Blends.” Projected completion date was September 22, 2023; research reporting is forthcoming. More information about this study can be found at: <https://highways.dot.gov/research/projects/improving-compatibility-waste-plastic-and-asphalt-binder-theoretically-justified>

Even if most of the effort is currently devoted to mastering the wet and dry processes, other alternative processes are likely to emerge in the future:

- Pre-coating of aggregate could improve absorption for highly absorptive aggregate, as well as the resistance to moisture damage (adhesion without the need for anti-stripping agents). Such a process would eliminate binder storage stability issues and avoid potential modifier compatibility issues.
- DOE Advanced Research Projects Agency-Energy (ARPA-E) project to thermally co-process polymer waste and liquid blending agents (e.g., oil medium) to generate refinery or petrochemical feedstocks and building materials (e.g., asphalt-compatible materials), entitled “Polymer/Oil Co-Processing to Yield Liquid Products”, award number DE-AR0001360. More information on this project can be found at: https://www.arpa-e.energy.gov/sites/default/files/2022-01/05.%20Hazard_PolymerOil%20Co-Processing%20to%20Yield%20Liquid%20Products%20.pdf

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Wet Processed Plastics in Asphalt

Case Study

C.J. DuBois

HAYLEY BROWN

CRISTINA SERRAT

Dow, Inc.

INTRODUCTION

The Global Plastics Alliance (GPA), a collaboration among global plastics industry associations representing plastic material suppliers and converters in countries all over the world, carried a survey and analysis on overall plastics flow in a circular economy with a focus on plastics waste management and treatment. Figure 1 shows an illustrative diagram of the flow and elements. The results indicated that the United States generated 34.5-MM metric tons of post-consumer plastics waste and collected almost 34 MM metric tons. The report also mentions that total volumes for recycling, energy recovery, and disposal have remained relatively stable over the past few years. Some recycling streams are rich in thermoplastic polymers, like plastomers, which have been used as asphalt modifiers in the past without success (1).

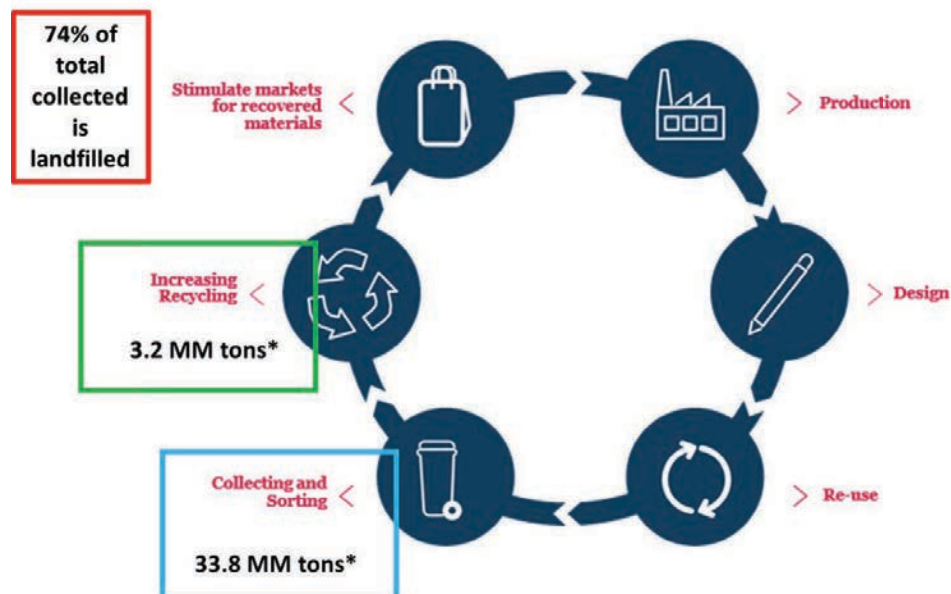


FIGURE 1 Flow diagram of a circular plastics economy and U.S. data on collection and post-treatment of plastic waste.

More recently, the use of recycled plastics in asphalt mixtures has triggered the interest of both the plastics and asphalt pavement industries (2). In 2020, at the time of the session on which this circular is based, there was bipartisan Congressional support for use of these materials, and key stakeholder groups such as the Asphalt Institute (AI), the National Asphalt Pavement Association (NAPA) and the National Center for Asphalt Technology (NCAT) have kicked-off workgroups. Moreover, in 2020, the Federal Highway Administration (FHWA) called for proposal submissions for a 3-year Exploratory Advanced Research Program on the Compatibilization of Waste Plastic to Enhance Mechanical Properties of Asphalt Cement. If post-consumer recycled (PCR) plastic packaging could deliver improved performance for asphalts and at the same time reduce the waste footprint with added cost benefits, the overall gains for the environment and both industries would be significant.

To initiate validation of some of the technical hypotheses behind the performance improvements, Dow began to study recycled polyethylene-rich compositions in asphalt binders, not only in the lab but also in the field. In this work, we present lab and field studies in which RPM asphalt met AASHTO M320, including upper, intermediate, and lower temperature tests, as well as AASHTO M332, through formulating blends with a RET compatibilizer. The technical learnings and the field experience gained with the initial RET-enabled demonstration projects in the United States with recycled polyethylene-rich compositions (RPE) were leveraged for additional demonstration projects in Bulgaria and Mexico.

TYPES OF POTENTIALLY RECYCLED PLASTICS

ASTM D7611 identifies various plastic products using the Resin Identification Coding System, or RIC (3). The goal of this labeling system is to serve as a tool to assist in sorting various plastics during the recycling process. The code does not necessarily mean the material can be recycled. Figure 2 provides examples of the seven major classes of coded materials.

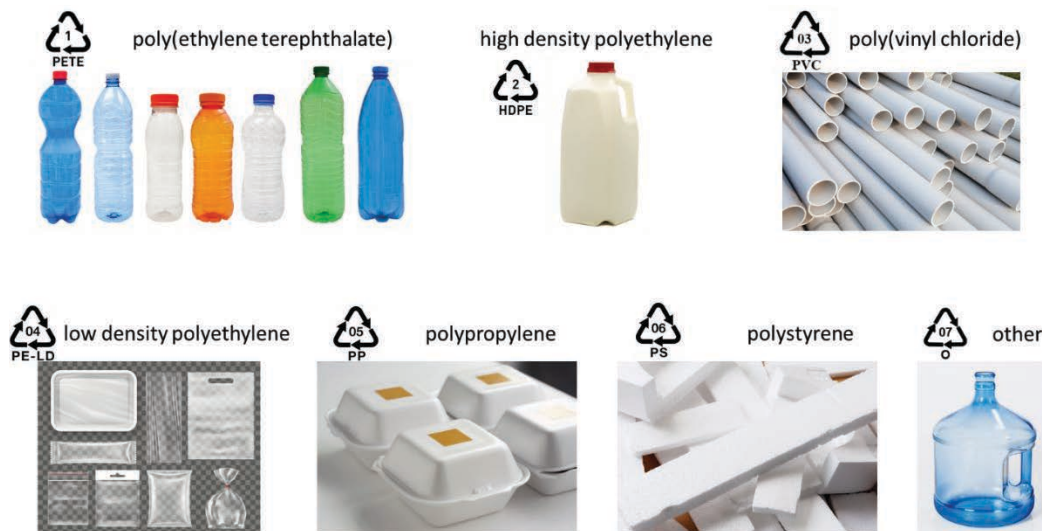


FIGURE 2 Major classes of plastics with corresponding RICs.

Plastic products designated with a “1” are based upon poly (ethylene terephthalate) (PETE), and typical applications using this material include fibers for clothing, liquid and food containers, thermoformed products, and tire cord. Materials designated with a “2” are high-density polyethylene, or HDPE, and include products such as rigid plastic bottles, corrosion-resistant piping, geomembranes, and disposable personal protection equipment suits. Poly (vinyl chloride) has a “3” designation and is used in the construction industry for pipes, siding, and flooring, and wire and cable insulation. Low-density polyethylene is designated with a “4” and includes applications such as flexible packaging. Plastic products designated with a “5” consist of polypropylene. Polypropylene is often used in applications requiring a flexible hinge, such as clamshell packaging. Resins listed with a “6” are polystyrene and commonly are used in expanded foam applications such as packaging supports. The last class, other, uses the “7” designation and consists of multiple classes of plastic resins. A common example would be polycarbonate, which is used in office water bottles (4–6).

The Environmental Protection Agency reports municipal solid waste inputs into landfills. The seven RIC classes are broken down by percentage in Figure 3 (7). If we deselect materials with MPs above 135°C that have not undergone chemical processing, only polyolefin-rich streams remain, the polyethylenes and polypropylene, which account for approximately 60% of the plastic resins entering municipal solid waste. The asphalt industry has worked with this class of materials for many years as they are elastomers.

Others have reviewed the significant amount of effort to incorporate to modify asphalt with recycled plastics that have taken place since the 1990s (8). As polyolefin resins behave as elastomers, separation, elastic properties, and cracking susceptibility (fatigue and thermal) are of concern. One example of a technology with mixed results utilizing polyethylene-based recycled materials was Novophalt, which required a specialized blending unit at the mix plant to mitigate separation (9–14). One way to more efficiently process modifiers into asphalt binder is to use a compatibilizer, such as a RET, that eliminates separation and allows the modified binder to pass all performance specifications including those challenging for a elastomer to meet alone.

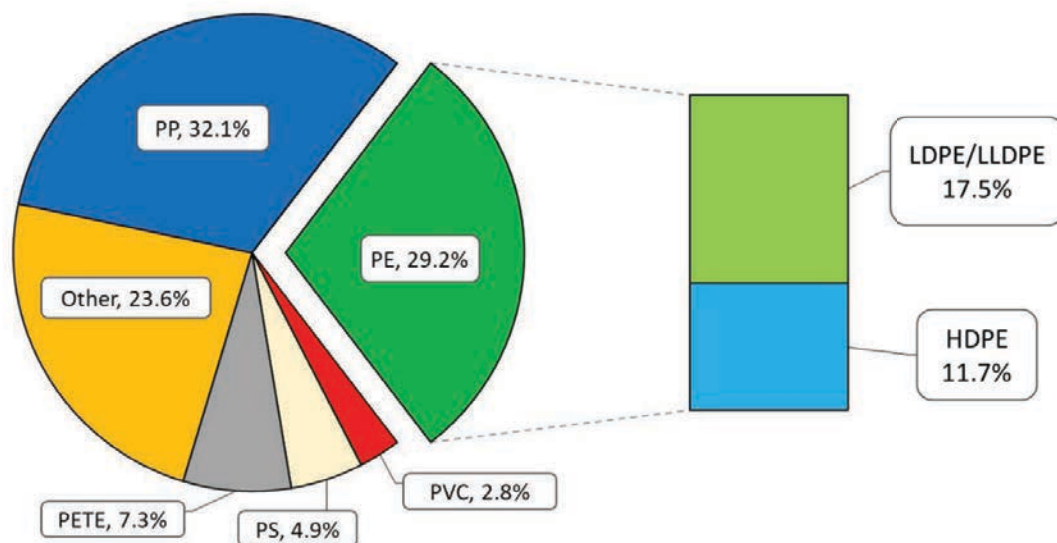


FIGURE 3 Breakdown of plastic content in municipal solid waste.

OVERVIEW OF RET TECHNOLOGY

RET is a class of polymeric modifiers based on ethylene copolymerized with a variety of polar monomers to balance of processability, polarity, and reactivity to modify asphalt. Table 1 summarizes some physical properties of available base resins.

Using glycidyl methacrylate (GMA) to introduce reactive epoxy side groups gives these polymers the ability to react with a wide array of functional groups in asphalt binders, as shown in Figure 4 (15). As such, RET can enhance the performance of asphalt binder at very low loadings, typically less than 2 wt%. When formulated with poly(phosphoric acid), PPA, as a co-reactant, the reaction occurs rapidly to increase high-temperature performance, as illustrated in Figure 5. This modification occurs with low mixing energy and does not require the use of a high shear mill to disperse the polymer. Additionally, the resulting modified binder is storage stable after reaction and does not exhibit separation once mixing is stopped.

As RET is an ethylene-based polymer, it was hypothesized that it could also provide physical miscibility with poly(ethylene) or poly(ethylene) -like materials and improve compatibilization by mitigating separation with asphalt. To test this hypothesis, a series of screening studies were conducted.

TABLE 1 ELVALOY RET

ELVALOY™ RET Resin	Reactivity	Density (g/cm ³)	Melt Index (190°C/2.16 kg)	Melting Point (°C)
AM	Low	0.94	12	72
4170	High	0.94	8	72
5160	Low	0.95	12	80
5170	High	0.95	8	82
EP 1170	Low	0.95	100	80
EP 1177	High	0.94	75	72
EP 1178	Low	0.94	25	61

NOTE: ™ = Trademark of The Dow Chemical Company (Dow) or an affiliated company of Dow.

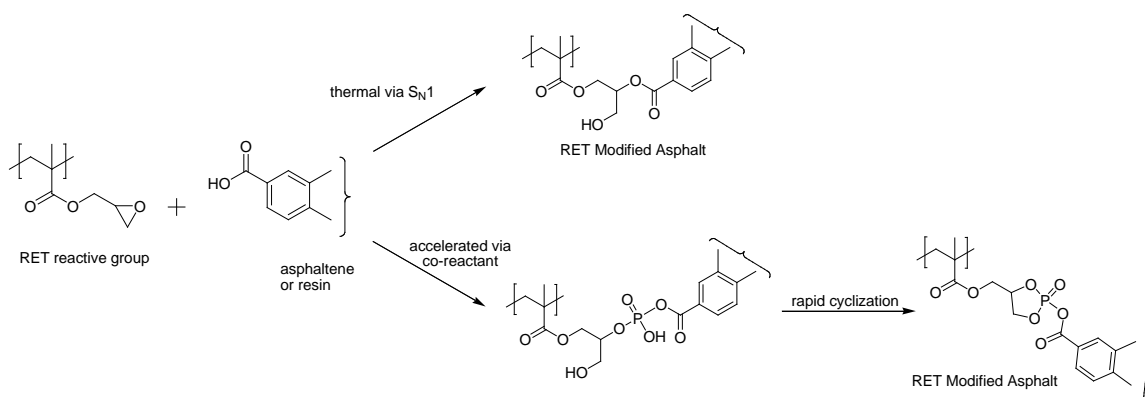


FIGURE 4 Postulated reaction mechanisms for RET with and without PPA co-reactant.

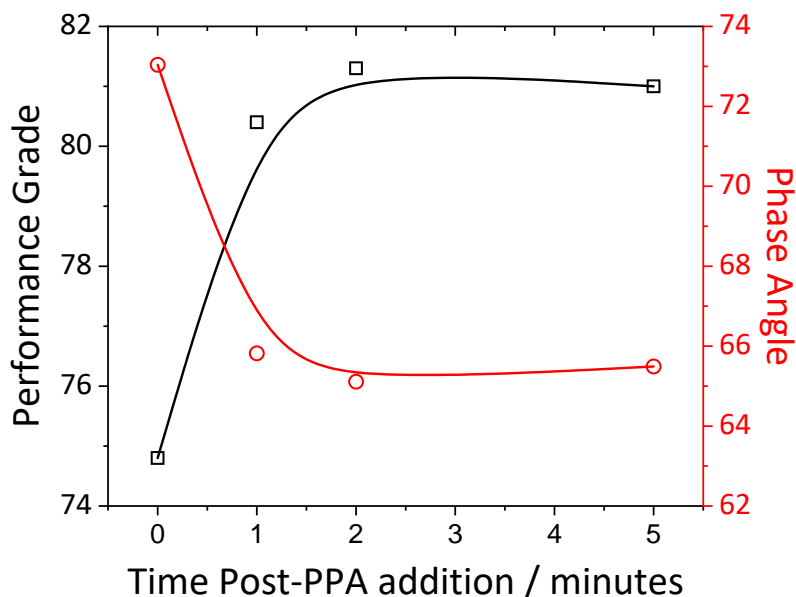


FIGURE 5 Impact of ELVALOY RET on asphalt binder performance (1 wt% ELVALOY EP 1170 and 0.2 wt% PPA mixed with binder at 165°C).

SCREENING STUDIES

A screening study was undertaken to determine if RET could serve as both a compatibilizer and improve performance gaps plastomers traditionally have as binder modifiers. The asphalt binder was a PADD III Valero PG 64-22. The recycled resin used in this portion of the study was a commercially available Natura PCR (LLDPE-rich) from Avangard Innovative. Dosages for it were either 1.5 or 3.0 wt%. Dosages of ELVALOY RET were either 0.9 or 1.8 wt%. All states except for the SBS contained 0.2 wt% PPA. SBS dosage was fixed at 1.8 wt% with 0.2 wt% BGA (Ergon Asphalt and Emulsions, Inc.) as the sulfur donor. The labeling system for the formulations was the dosage of the recycled resin followed by the dosage of the elastomer (i.e., a 3 wt% recycled resin and a 1.8 wt% RET would be listed as 3/1.8).

The first test of the recycled resin formulations was to study 48-h separation values using ASTM D7173 with results shown in Figure 6. The unfilled bars correspond to the separation values of the PCR-only samples were very high at greater than 40°C for each. As expected, the RET samples have no separation. The diagonally slashed bars below correspond to various combinations of PCR and RET and are highlighted in the two boxes with the RET-only samples. When the PCR/RET dosages are balanced as with the 1.5/0.9 and 3/1.8 samples, no separation is observed confirming RET can serve as a compatibilizer for polyethylene-rich PCR. The sample containing SBS showed some improvement in the separation performance by reducing it by approximately 18°C, but still would be considered a failure for states requiring lower separation values.

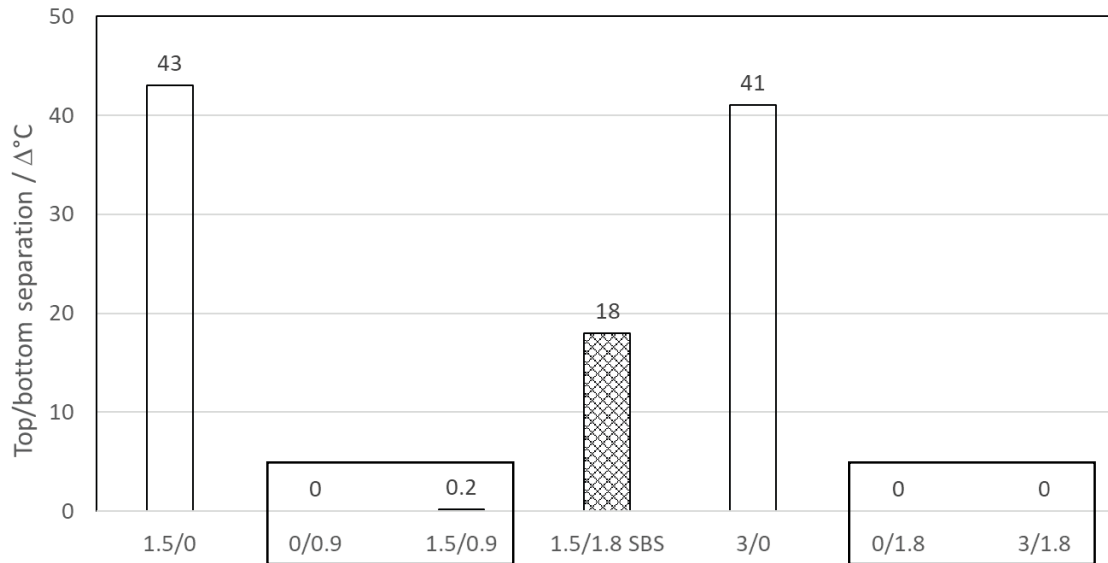


FIGURE 6 ASTM D7173 separation test results for various combinations of recycled polyethylene with ELVALOY RET or SBS.

Upper continuous grade measurements of the various formulations are summarized in Figure 7. The unfilled bars again correspond to the PCR-only samples. The 1.5 wt% PCR dosage increased the upper continuous grade from 69.4°C, the unmodified binder, by approximately 10°C, and the 3.0 wt% PCR dosage increased it to 82.5°C. The RET-only samples (solid gray bars) increased this property to 79.4 and 89.6°C using dosages of 0.9 and 1.8 wt%, respectively. The balanced dosage combinations of PCR/RET (diagonally slashed bars) increased the upper continuous grade compared to the states versus the samples that contained only one of those modifiers. The control with 1.8 wt% SBS and PCR (cross-hatched bar) had similar performance to that of the 1.5 wt% PCR plus 0.9 wt% RET. The reactive polymers, RET and SBS, increased the upper continuous grade at a higher rate per percent than the plastomers. Higher values are desired in the linear viscoelastic domain as that reflects how well the polymer is influencing the asphalt binder (16–17).

The Texas-539C elastic recovery measurements are summarized in Figure 8. Note that these experiments are performed at 10°C. Both PCR-only samples failed due to ductile failure during the elongation, as noted in Figure 9. The RET-only samples (solid gray bars) displayed elastic recovery values of 60 and 70% for dosages of 0.9 and 1.8 wt%, respectively. The balanced dosage combinations of PCR/RET (diagonally slashed bars) both had reductions of the values by 7.5%. The control with 1.8 wt% SBS and PCR (cross-hatched bar) had an elastic recovery value of 60%.

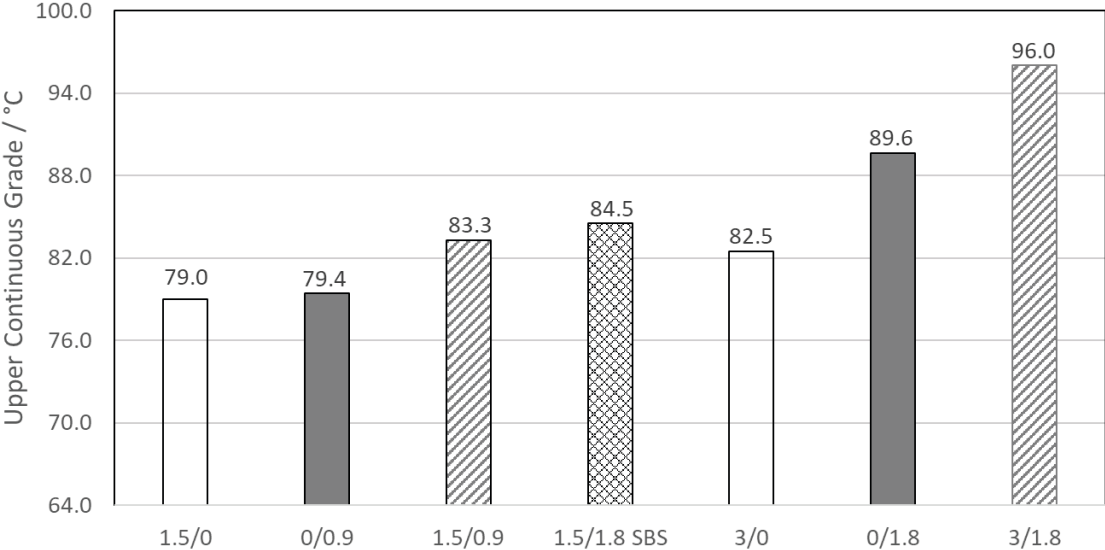


FIGURE 7 Upper continuous grade measurements using AASHTO T315 for various combinations of recycled polyethylene with ELVALOYRET or SBS.

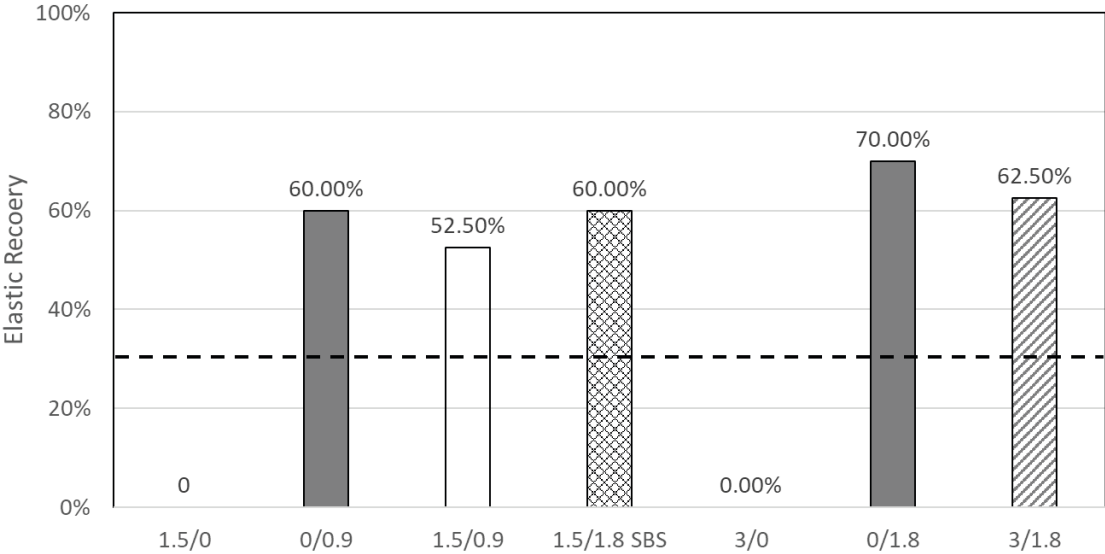


FIGURE 8 TEX-539C elastic recovery comparison for various combinations of recycled polyethylene with ELVALOY RET or SBS.

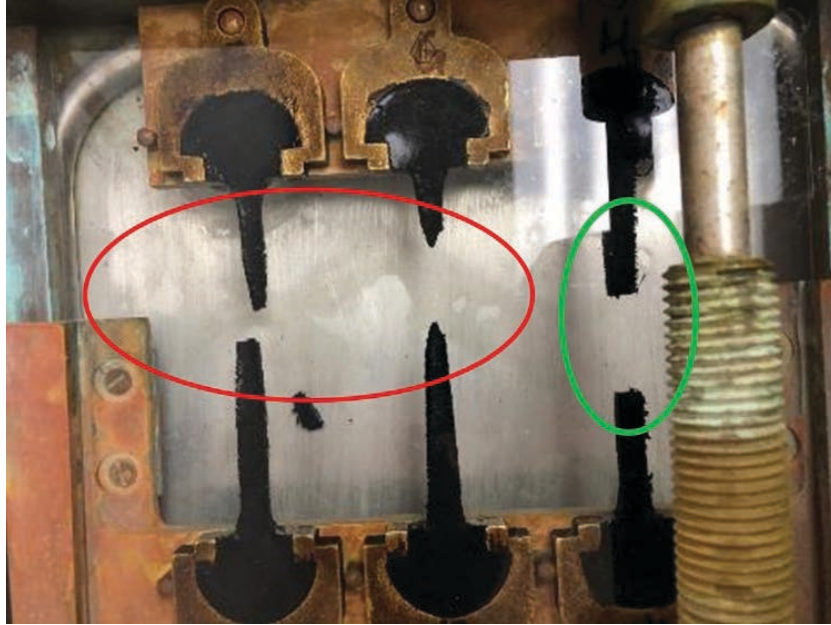


FIGURE 9 Failure of the PCR-only samples during elongation.

Phase angle response the performance grade is shown in Figure 10. The unfilled bars again correspond to the PCR-only samples. The 1.5 wt% 3.0 wt% PCR samples demonstrated phase angles in the low 80 degrees region, which is only a slight improvement over the unmodified binder (85 degrees). The RET-only samples (solid gray bars) displayed significantly reduced phase angles of 76° and 62° with dosages of 0.9 and 1.8 wt%, respectively. The balanced dosage combinations of PCR/RET (diagonally slashed bars) had phase angles more like the RET-only than the PCR-only values. This effect further demonstrates that the RET compatibilizes the PCR to a much higher degree than SBS, which had a phase angle of 79°. A decrease in phase angle implies increased elastic behavior.

Nonrecoverable creep compliance values of the various formulations are summarized in Figure 11. Except for the 1.5 wt% PCR sample, which met a “V” grade, all formulations met an “E” grade at 67°C. The combination of PCR with either RET or SBS had similar J_{nr} values as the RET-only samples. Lower values of J_{nr} are desired as traffic levels increase to avoid rutting failures of the pavement at the specified grade temperature (18).

Percent recovery values of the various formulations are summarized in Figure 12. The unfilled bars again correspond to the PCR-only samples. Both loadings of PCR demonstrated low percent recovery values that fall below the “29 line” indicating they behave more similarly to unmodified than modified binders. The RET-only samples (solid gray bars) displayed percent recovery values of 62% and 84% with dosages of 0.9 and 1.8 wt%, respectively. The balanced dosage combinations of PCR/RET (diagonally slashed bars) had %R values more like the RET-only samples. This effect further demonstrates that the RET compatibilizes the PCR to a much higher degree than SBS which had %R values of 52. Of note is the PCR/SBS formulation had higher upper continuous grade performance, higher elastic recovery values, but lower percent recovery. High percent recovery values indicate more elastic behavior (18).

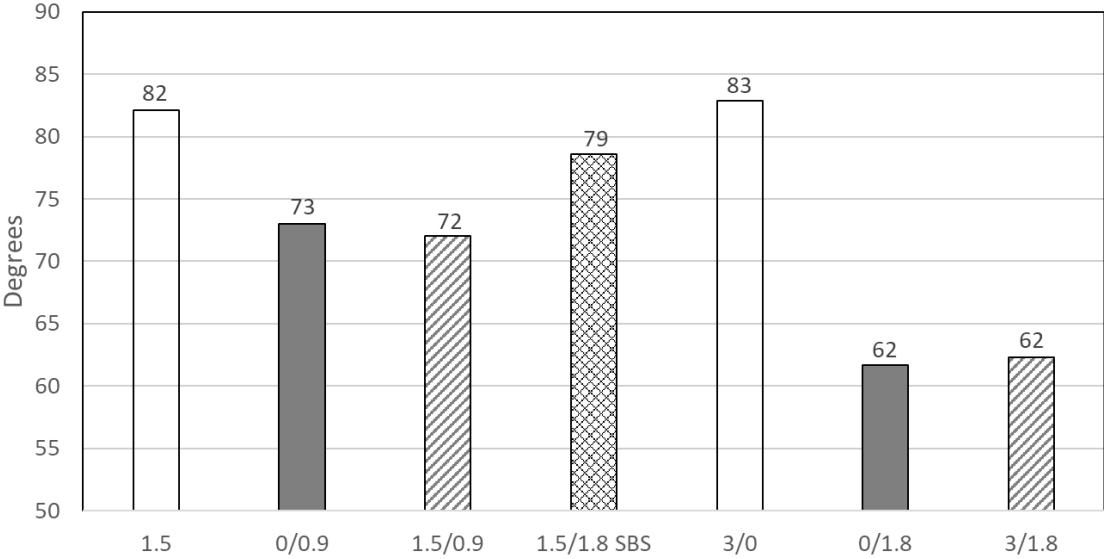


FIGURE 10 Phase angle comparison for various combinations of recycled polyethylene with ELVALOY RET or SBS.

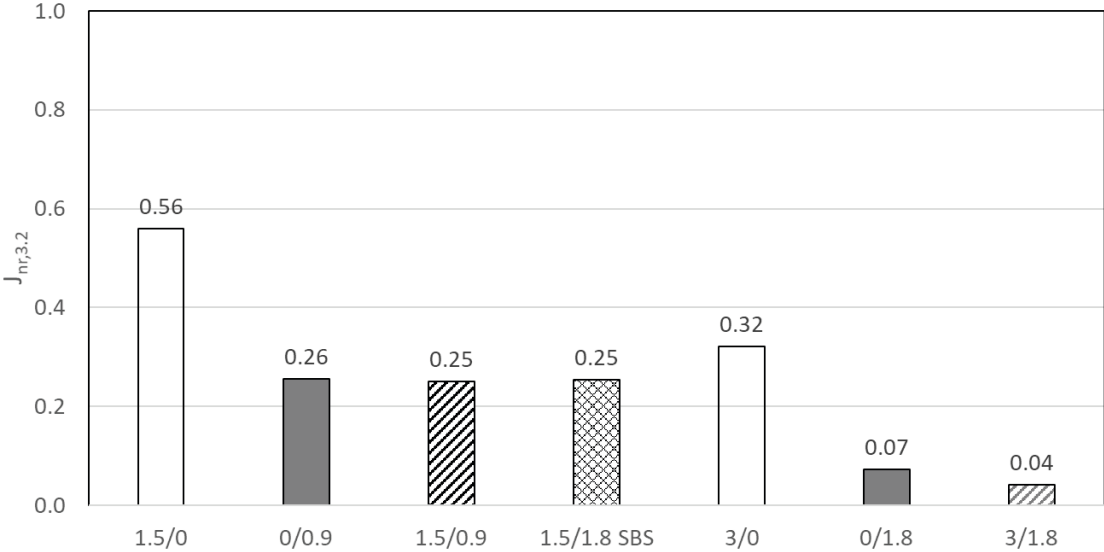


FIGURE 11 $J_{nr,3.2}$ comparison at 67°C for various combinations of recycled polyethylene with ELVALOY RET or SBS.

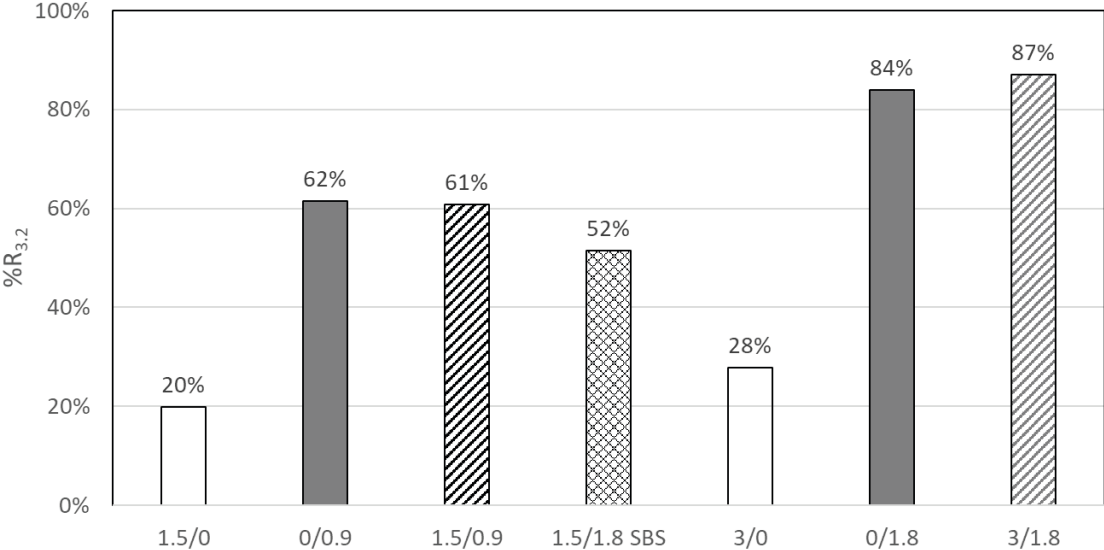


FIGURE 12 $\%R_{3,2}$ comparison at 67°C for various combinations of recycled polyethylene with ELVALOY RET or SBS.

Intermediate temperature performance ($G^* \times \sin \delta$) was tested at 25°C. All formulations had lower values than the allowed maximum of 5000 kPa as shown in Figure 13. The PCR-only samples had the highest values, and the RET-only samples had the lowest values. The combination of PCR and RET had values more like the RET-only samples. The PCR/SBS combination was closer in values to the PCR-only samples.

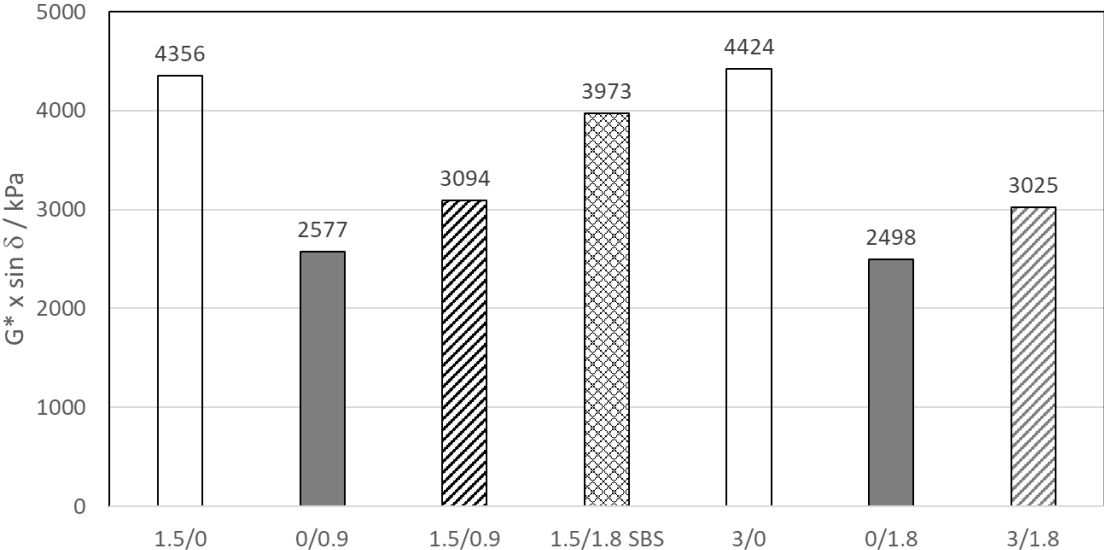


FIGURE 13 $G^* \times \sin \delta$ comparison at 25°C for various combinations of recycled polyethylene with ELVALOY RET or SBS.

Low-temperature BBR comparisons at -12°C are summarized in Figure 14 and Figure 15. Stiffness values for all samples were significantly under the maximum allowed 300 MPa. No clear trend is observed for the samples. Both PCR-only samples were slightly higher than the RET-only samples with the highest state of 3 wt% having the highest stiffness. There were no differences in the stiffness values between the two RET-only samples, even when doubling the dosage from 0.9 to 1.8 wt%. The combination of PCR/RET with the highest PCR had a lower stiffness value than the PCR/RET combination with the lowest PCR.

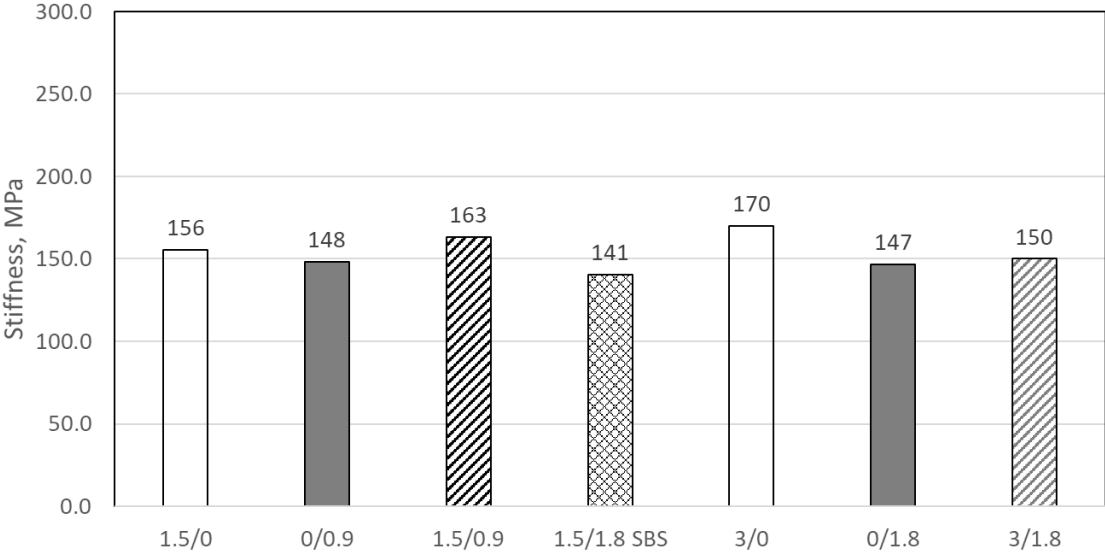


FIGURE 14 Stiffness properties at -12°C for various combinations of recycled polyethylene with ELVALOY RET or SBS.

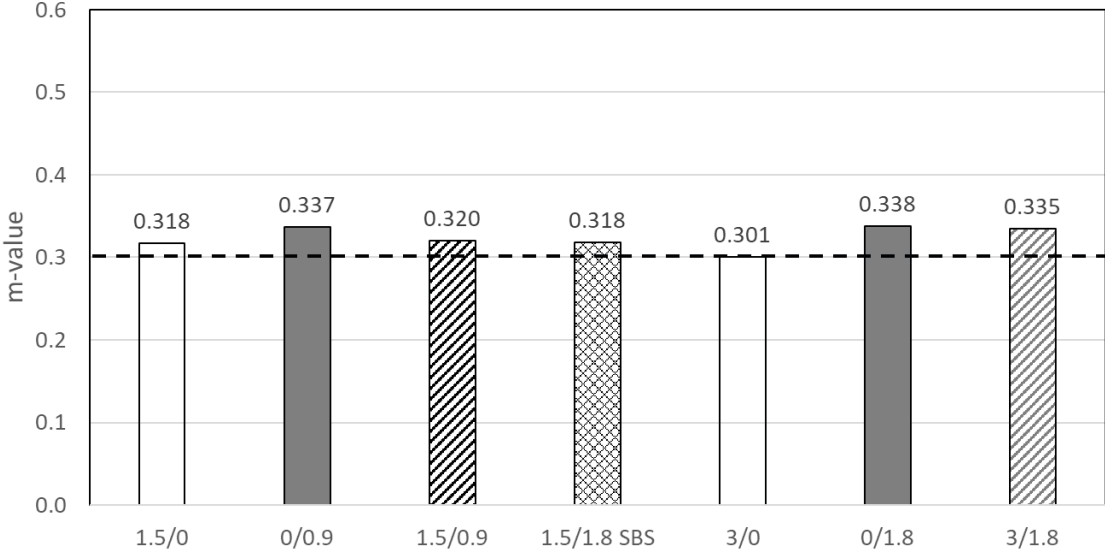


FIGURE 15 *m*-value properties at -12°C for various combinations of recycled polyethylene with ELVALOY RET or SBS.

No clear trend was observed with the m -values results at -12°C . The PCR-only controls had the lowest values and increasing the dosage from 1.5 to 3.0 wt% reduced the m -values slightly. The combination of PCR/RET with the highest PCR had the highest m -value compared to the lowest PCR/RET combination.

Low magnification epi-fluorescence optical images of the binder without polymer modifier and the highest RET and PCR/RET combinations are shown in Figure 16. No distinguishable differences between the base binder and RET-only sample are observed, indicating homogenous incorporation of the polymer modifier. The PCR-only sample displayed distinguishable domains of various diameters up to approximately $100\ \mu\text{m}$. The combination of PCR/RET demonstrated visibly smaller domains.

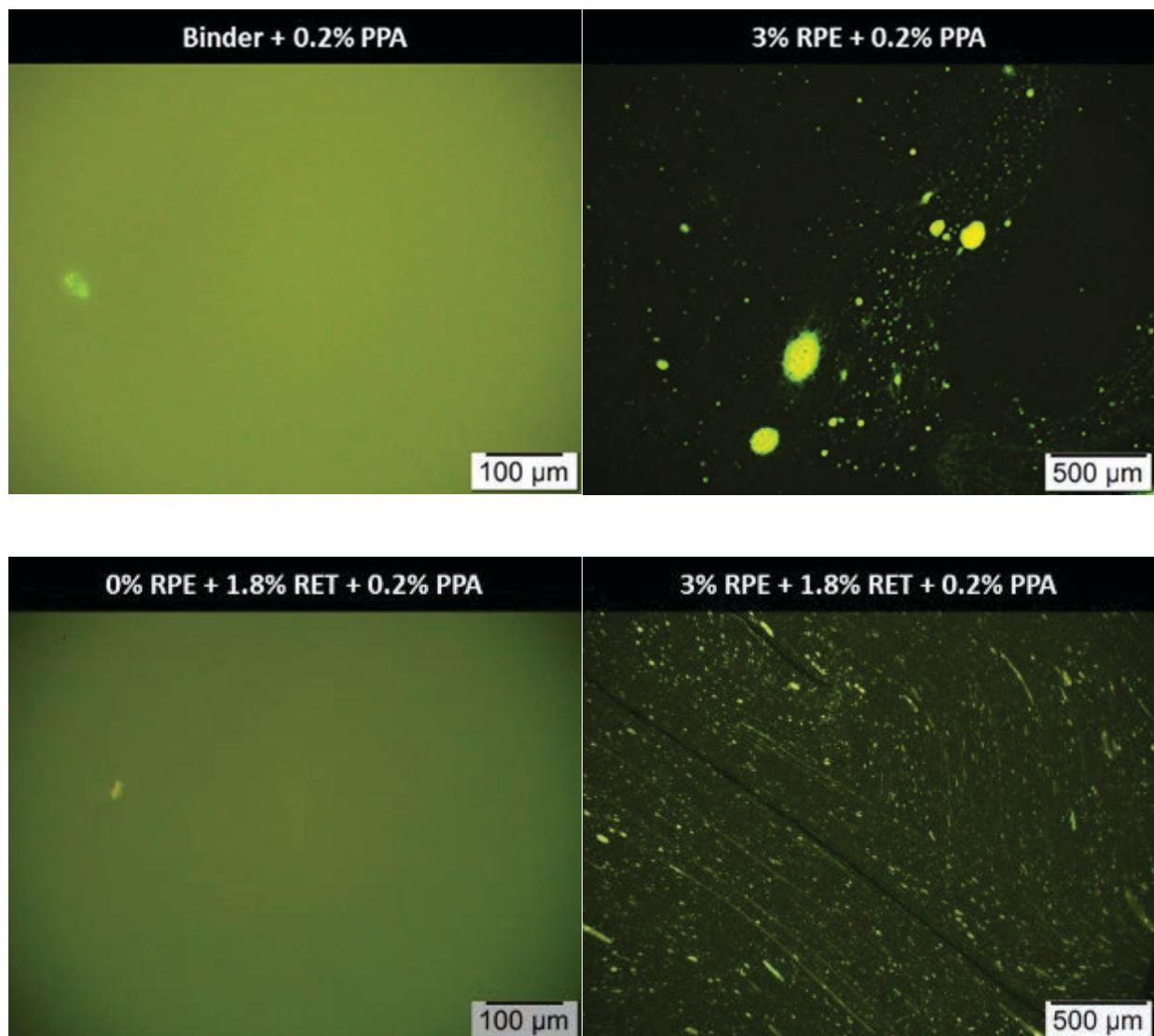


FIGURE 16 Fluorescence imaging showing domain sizes for different formulations with and without RPE.

TEXAS CASE STUDY

In January of 2019, Dow constructed two PMA roads (Plastics Road and Gulfstream Road) at a Freeport, Texas, facility using approximately 1,700 lb (1.5 wt% in binder) of commercially available Natura PCR (LLDPE) from Avangard Innovative. This amount of PCR corresponded to the equivalent weight of 120,000 plastic grocery bags. ELVALOY RET EP1177 was used as a compatibilizer with 0.6 wt% with 0.2% PPA as a co-reactant sourced from Innophos. The project called for a TX DOT PG70-22 binder which was supplied by Martin Asphalt. American Materials prepared the hot mix and Vernor Construction constructed the pavements. Mix design was Texas DOT type D (340-DG-D) using a 1.50-in. lift thickness. One street was paved as an overlay, as shown in Figure 17, and the other was a new lift. Total binder content was 5.2%, with 19.1% RAP and a limestone/dolomite aggregate.

Table 2 summarizes the binder properties for the project, which met all Texas DOT PG 70-22 performance criteria. Of note was the Natura PCR allowed the dosage of the ELVALOY RET to be reduced by 50% from 1.2 wt% to 0.6 wt% while still significantly exceeding the required elastic recovery requirement.

MICHIGAN CASE STUDY

In August 2019, Dow with several industry partners used recycled plastic in modified asphalt pavements on four Midland County Michigan roads (total of 6 lane-miles), as well as parking lots with a combined total of 30,500 square yards at the Global Dow Center in Midland, Michigan and at Saginaw Valley State University in Kochville Township, Michigan. The projects used



FIGURE 17 January 2019 photo of partially completed project in Freeport, Texas.

TABLE 2 Results of Various AASHTO Tests for Texas DOT PG 70-22 Specification

Texas DOT PG 70-22		1.5% Natura PCR + 0.6% ELVALOY RET EP1177 + 0.2% PPA	
Property	Requirements	Required	Field Sample
ORIGINAL			
Rotational viscosity, Pa·s	135°C	3.0 max.	< 3
Dynamic shear, kPa	At grade temperature	1.00 min.	1.13
Elastic recovery, %	10°C	≥ 30%	50
Separation	48 h, 163°C	—	—
Rolling Thin Film Over (RTFO)			
Dynamic shear, kPa	At grade temperature	2.20 min.	3.6
Pressure Aging Vessel (PAV)			
100°C, 20 h, 300 psi			
Dynamic shear, kPa	At test temperature	25°C	
		5,000 max.	3,100
Creep stiffness, MPa	At test temperature	-12°C	
		300 max.	185
<i>m</i> -value		0.300 min.	0.312

more than 10,400 lbs of recycled plastic, which is the equivalent weight to over 769,500 single-use grocery bags. A breakdown of each location is as follows:

- Waskevich Lane in Larkin Township: 2 lane-miles and incorporating more than 1,600 lbs of recycled plastic (equivalent in weight of more than 114,000 plastic grocery bags); 1.5-in. overlay for an entrance into a large subdivision with relatively high daily local traffic.
- Mid-Bay County Line Road in Larkin Township: 2 lane-miles and incorporating more than 1,600 lbs of recycled plastic (equivalent in weight to more than 114,000 plastic grocery bags); 2-in. overlay with rural farm–residential traffic pattern.
- Julie Ann Drive in Larkin Township: one lane-mile and incorporating more than 800 lbs of recycled plastic (equivalent in weight to more than 57,000 plastic grocery bags); 1-in. ultrathin overlay with urban/residential traffic pattern.
- Badour Road in Bullock Creek: covering one half lane-mile and incorporating more than 400 lbs of recycled plastic (equivalent in weight to more than 28,500 plastic grocery bags); 2-in. overlay with rural farm–residential traffic pattern.
- The Global Dow Center parking lot in Midland: 16,000 yd² incorporating more than 2,300 lbs of recycled plastic (equivalent in weight to more than 164,000 plastic grocery bags).
- The Saginaw Valley State University parking lot in Kochville Township: 14,500 yd² incorporating more than 4,100 lbs of recycled plastic (equivalent in weight to more than 292,000 plastic grocery bags).

Figure 18 illustrates the pre-construction distresses at the Midland County road projects. Heavy fatigue and thermal cracking were observed. Traffic levels for each site varied in level



FIGURE 18 Pre-construction photos of some of the Michigan construction sites showing high levels of pavement distress.

between a mix of residential, light truck, and heavy equipment. Typical binder requirements for these pavements called for either unmodified PG 58-28 or a PPA-modified PG 64-28M.

Post-industrial recycled plastic was utilized, which consisted of polyethylene-rich material from a packaging film application containing approximately 25% engineering resins. The asphalt binder targeted a Michigan DOT PG 64-28P specification using 1.2 wt% recycled polyethylene, 1.2 wt% ELVALOY RET EP1177, and 0.24 wt% PPA. The hot mix for the projects used a 12.5-mm Michigan DOT Type 4C Marshall mix design except for one of the Midland County roads, which used a 4.75-mm ultrathin sand mix for one road. Binder content was 4.32% virgin binder with 15% RAP.

Table 3 summarizes the binder performance of the commercially produced sample with recycled polyethylene vs. a commercially prepared 1.5% PPA control that would typically be used on these types of projects. Different base asphalt was used for each material, which complicated comparisons. While viscosities were similar between the two binders, the $G^*/\sin \delta$ of the PMA was found to be lower than that of the PPA-modified control. Significantly higher elastic recovery was measured for the PMA-modified samples at 70% versus 32% for the PPA control. Figure 19 provides photographs of several projects post-construction.

TABLE 3 Comparison of Binder Properties for Binder Used in the Field Projects and a PPA-Modified Control

Michigan DOT PG 64-22P				
Property		Requirements	Field Sample	PG 64-28M (PPA control)
ORIGINAL				
Rotational viscosity, Pa-s	135°C	3.0 max	0.5	0.5
Dynamic shear, kPa	At grade temperature	1.00 min.	1.02	1.21
Elastic recovery, %	10°C	≥ 60%	70	32
Separation	48 h, 163°C	≤ 2°C	9	0.5
RTFO				
Dynamic shear, kPa	At grade temperature	2.20 min.	2.89	3.04
PAV				
Dynamic shear, kPa	At test temperature		22°C	
		5,000 max.	3,300	3,100



FIGURE 19 Post-construction photos of the various project sites.

SUMMARY AND CONCLUSIONS

Several field projects that included different sources of asphalt, different recycled plastics sources, and construction partners showed that formulation of recycled plastic and an elastomeric reactive terpolymer passed state and county binder specifications and could be processed in polymer modification and hot mix plants with no noticeable differences. The execution of the pavement jobs was deemed in all cases as not different from traditional projects by construction personnel (19).

Since the initial draft of this E-Circular, additional work has occurred including laboratory experiments exploring cracking tests (20); field projects at NCAT in 2021 (21), at the University of Missouri in 2021 (22), at MnROAD in 2022 (22), and in Colorado in 2022 and 2023 (23); and a study on microplastics generation (24).

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DISCLAIMERS

The contents and opinions of this paper reflect the views of the authors, who are solely responsible for the facts and the accuracy of the data presented herein. The contents of this paper do not necessarily reflect the official views or the policies of any agencies.

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Dry Processed Plastics in Asphalt

Case Study

JEAN-PAUL FORT

Jean-Paul Fort Technical Services LLC

SUMMARY

The direct incorporation of recycled polyethylene (rPE) during the manufacturing process provides the asphalt mix with specific properties that make it both stiffer and durable. These performances allow for specific applications, including high modulus mixes for structural layers or rut resistant heavy-duty surface courses. Practicality is another advantage of the process as the dry additive is introduced in pre-weighed bags or through a dry metering system, preventing a change of binder, particularly noteworthy for small tonnages. In the dry process rPE plays a double role: particles adhere to mineral surfaces, interlocking and reinforcing the mineral structure; while others disperse in the binder increasing its viscosity, acting as modifiers. However, for the successful development of the process, the full environmental benefits of recycling plastics must be accounted for.

INTRODUCTION

The idea of using recycled plastic to increase the stiffness of asphalt mixes is almost as old as the development of PMA binders. In France, the process was initiated in the 1970s with the recycling of phone cable sheaths made from low-density polyethylene (LDPE). Ground recycled LDPE was incorporated during the mix manufacturing process as an alternative to hard binders for producing “Enrobés à Module Élevé,” high modulus asphalt concrete (HMAC). HMACs (Figure 1) are usually designed with hard asphalt binders at relatively high content, conferring upon them unique performance properties: high modulus, excellent resistance to permanent deformation, and yet with good durability and fatigue resistance (1). The idea of obtaining good fatigue response without jeopardizing resistance to rutting is consistent with the “Balanced Mix Design” approach. HMACs are also in line with the “Perpetual Pavement” concept, where material formulation is adapted to the function of the layer: a “rich-bottom” fatigue resistant base, a rut resistant intermediate course, and the well named wearing course; HMACs are fatigue resistant and rut resistant layers rolled into one. The use of HMACs has also been extended to heavy-duty surface courses to reduce rutting.

- HMACs have been designed for strengthening new pavements or overlays that are subjected to severe flexural stress such as highway slow lanes, city bus lanes and heavy-duty



FIGURE 1 Photographs of HMAC projects in France: (a) A-31 Highway, Toul-Langres, France (150 mi slow and lanes, 270,000 tons rPE HMAC base course) and (b) Tramway Lane, Clermont-Ferrand, France (heavy-duty rPE HMAC wearing course).

industrial pavements, etc. Thanks to their high structural value, HMACs are valuable where reduced thickness is required because of geometric constraints, such as urban thruways or motorways. They allow for cost-competitive pavement structures and permit the reduction of a project's environmental footprint by saving natural resources, energy and cutting emissions.

- Diverting plastics from landfills and taking advantage of their attributes adds to HMAC's environmental credits. LDPE also increases fuel resistance, which make rPE HMACs particularly applicable for truck parking lots or airport taxiways and aprons.
- Modification with recycled LDPE can be achieved by prior blending into the asphalt binder, known as "wet process" technology. Another cost-efficient method is the "dry process" where recycled LDPE is incorporated as a solid additive during the asphalt mixture manufacturing process. This technology is presented here.

DRY PROCESSED PLASTICS IN ASPHALT

Production

LDPE is part of the polyolefins family, which are saturated polymers of ethylene (C₂H₄), propylene (C₃H₆) and butene (C₄H₈). The absence of double bonds confers upon them good resistance to oxidative aging. However, they have a low chemical compatibility with bitumen and hence are difficult to disperse without separating, which is exacerbated by their lower density. In the "wet process," blend stability is improved with additives, but manufacturing becomes more complex and expensive.

The dry process provides an economical and flexible alternative by directly incorporating the shredded polyolefins into the hot mixing plant (Figure 2). In batch mixing plants, pre-weighted meltable bags are introduced into the pug mill; in continuous plants, bulk recycled plastic is



FIGURE 2 Addition of rPE at asphalt production facility: (a) rPE meltable bag introduced in a batch plant and (b) rPE big-bag dosed with hopper in continuous plant.

proportioned volumetrically by a feeding auger or by weight with a blower. The dry process eliminates the need for an additional tank and the produced mix can be modified as local traffic conditions require - intersections, slow lanes, toll lanes, etc. - preventing multiple and costly binders to be used for small tonnages.

In the first stage, polyolefins, mainly rPE, are dispersed and melted in the hot aggregates and the bitumen is then injected, partly “dissolving” them. Depending on the nature of polyolefins (low-density polyethylene, or mixture with other plastics) and particle size and shape (powder, fibers, tabs, granules, etc.), complex effects are obtained. Some polyolefin particles adhere to mineral surfaces, interlocking the mineral structure; others increase the mortar consistency, while others disperse in the binder, increasing its viscosity. As such, their role is structural reinforcement as much as binder modifier.

Dry Processed rPE Asphalt Mixtures Microstructure

The complexity of the structure of the “Dry Processed” rPE asphalt mixtures has been confirmed thanks to the microscopic method developed at the Danish Road Directorate (2). On thin sections cut from rPE asphalt mixes and studied by microscopy with incident UV-light as shown in Figure 3, the rPE phase appears yellow, the bitumen brown, and the mineral particles green. Relatively large rPE slivers can be seen still coating some aggregates and bridging the mineral structure where finer rPE particles are dispersed through the binder phase. This microstructure offers clues for some of rPE mixes characteristics:

- Larger rPE clumps interlock the mineral structure, reinforcing it;
- rPE particles swell by preferential absorption of binder’s light ends, raising its viscosity and mechanically increasing the effective binder film thickness; and
- The partial coating of mineral surfaces reduces moisture sensitivity and asphalt absorption, also contributing to binder film thickness.

Overall, the reinforcement of the mineral framework and stiffening of the binder phase explain rPE asphalt mixes’ stiffness moduli and rutting resistance, while the thicker effective binder is responsible for the good fatigue response, lower water sensitivity, and compactibility.

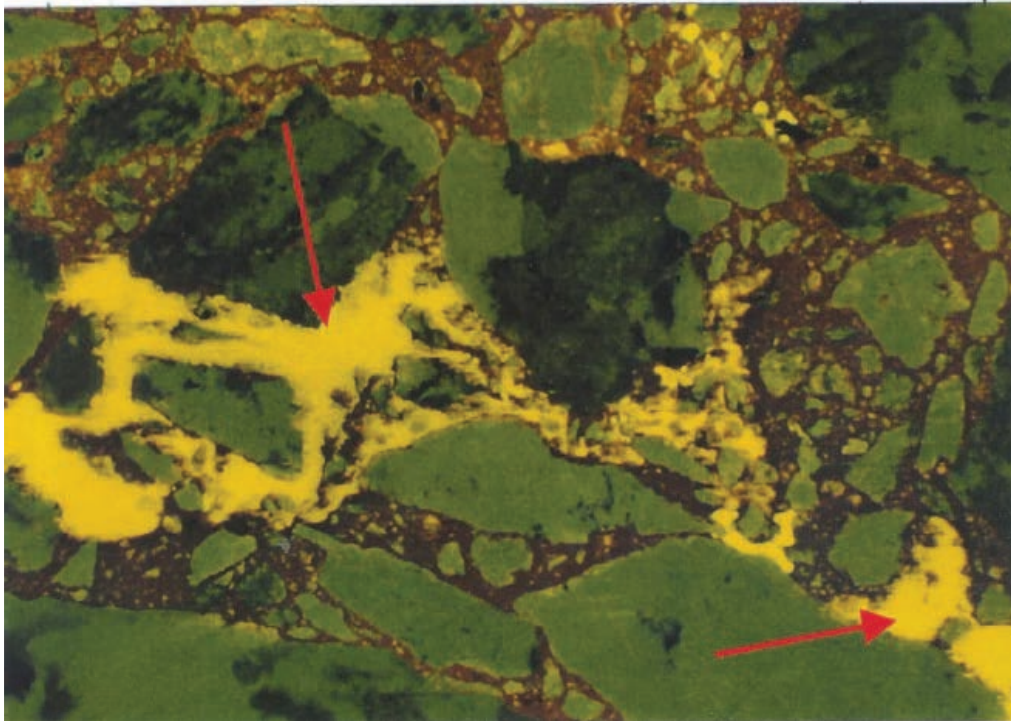


FIGURE 3 rPE-modified asphalt mix thin section (x40).

Design Principles

One consequence of the complexity of the blend is the impossibility of designing this composite uniquely from modified binder characterization; the effects of polyolefin modification are better evaluated by measuring the asphalt mix's performances.

In the dry process, the polyolefin proportion is usually between 0.3% and 1% by weight of dry aggregate. Depending on the required level of service (traffic, climate) and the position of the layer in the pavement structure, the dosage is adjusted by balancing rutting and cracking resistance performances. To account for the partial blending shown above, only half of the rPE introduced serves as binder replacement. The limiting factor is generally the risk of making the mix fragile at low temperatures and causing thermal cracking. When used as a structural layer, dynamic modulus and fatigue performance are evaluated.

Construction

Laying rPE asphalt mixes does not entail any difficulty, if temperature requirements are complied with, as the crystallization of the polyethylene network and stiffening is temperature dependent. High energy compaction must be implemented right behind the paver screed. Still, thanks to binder's greater effective film thickness, rPE HMACs are easier to compact than their hard binder base counterparts.

Polyolefins Selection Guidelines

One of the major challenges for the recycling of plastics in roads is the variability of the feedstock (Table 1), especially post-consumer sources which constitute by far the bulk of the plastic waste stream. Without considering the variable municipal waste stream, focusing solely on wire and cable recycling, the insulation scrap generated can include several constituents: low-density and high-density PE, cross-linked PE (PEX), Polypropylene (PP), Polyvinyl Chloride (PVC), and/or Teflon. Aluminum and copper wire debris are also common. PEX and PP won't melt easily in our mixes and would be considered more aggregate replacement rather than modifiers. PVC and Teflon generate harmful emissions when heated and shall be avoided. Last but not the least, the variability of the feedstock imposes processing and sorting costs that impact plastics recycling cost-efficiency.

Consequently, it is essential to have an efficient screening method in place for (1) eliminating potentially harmful components and (2) selecting plastics with MPs preferably below our production temperatures, that will have an impact on mixtures performances. The set of tests listed in Table 2 are easy enough to be implemented in field laboratories and will allow plants to accept or reject an incoming lot of recycled plastics. Another possible test is Differential Scanning Calorimetry that will precisely define the recycled plastics MP range. LDPE peaks will be located between 212°F and 270°F.

TABLE 1 Plastics Characteristics and Use in Asphalt Mixes

Denomination	Code	Density (g/cm ³)	MP (°F)	Use
Low-density polyethylene	LDPE	0.91–0.93	220–240	Modifier
Linear low-density polyethylene	LLDPE	0.91–0.94	240–320	Modifier
High-density polyethylene	HDPE	0.96–0.97	250–356	Modifier/filler
Polypropylene	PP	0.90–0.95	270–340	Modifier/filler
Cross-linked Polyethylene	PEX	0.90–0.95	Thermoset	Filler
Polystyrene	PS	0.96–1.05	410–480	Filler
Polyethylene terephthalate	PET	1.38–1.46	480–500	Filler
Polyvinyl chloride	PVC	1.1–1.45	212–500	Harmful

TABLE 2 Field Laboratory–Plastics Screening Procedure

Test Procedure	Limits	Comments
Gradation	85% Passing #4 (4.75 mm)	For good dispersion and melting
Moisture content	Dry to constant mass @ 80°C	< 5%
Float test in water @ 25°C/77°F	<ul style="list-style-type: none"> LDPE: 0.90–0.95 g/cm³ PVC: 1.1–1.4 g/cm³ 	≥ 95% float ratio Evidence if PVC present; proxy for MP (bar PEX)
Melting point	30 gr @ 340°F for 30 min	Visual

RPE ASPHALT DESIGN AND PRODUCTION TRIAL CASE STUDY, CINCINNATI, OH

In 2005, an rPE HMA Superpave design based on the dry process was, for the first time, developed and evaluated with North American performance testing methods at Colas Solution's Cincinnati, Ohio, location. Subsequently, a production trial took place in nearby Clermont County, albeit based on the project Marshall Design. The laboratory study control mix was an Ohio DOT Superpave 12.5 mm, 10-30 million ESALS, (N design = 100) using a polymer-modified PG 70-22M binder (Table 3).

Laboratory Asphalt Mix Performance Study

A "Balanced Mix Design" approach was adopted: rutting resistance versus low-temperature cracking susceptibility.

Rutting Susceptibility—Asphalt Pavement Analyzer

Once the recycled LDPE (rPE) source was selected, the next step was the determination of the percent of rPE required to impart the rutting resistance of the PG 70-22M control mix to non-modified PG 64-22 and PG 58-28 mixes. The laboratory mixed and compacted specimen's fabrication details are shown in Table 4 where 50% of the rPE incorporated was accounted as binder replacement. Dry mix times were increased to allow for the good dispersion of the rPE particles prior to binder blending.

TABLE 3 SuperPave 12.5 - 100 Gyration Control Mix

%	Size	Type
15	#7	Crushed Gravel
25	#8	Crushed Gravel
10	#9	Crushed Limestone
35	#10	Manufactured Sand Limestone
15	#10	Natural sand
5.8	n/a	PG 70-22M

TABLE 4 Mix Specimen's Fabrication Parameters

Design	Agg. Temp. (°F)	AC Temp. (°F)	Dry Mix Time (s)	Wet Mix Time (min)	Mixing Temp. (°F)	Curing Temp. (°F, 2 h)	Compaction Temp. (°F)
PG 64-22	325	295	30	1	310	295	290
PG 58-28	315	285	30	1	300	28	275
PG 70-22 P	340	310	30	1	315	305	300
PG 64-22 + X ¹ % LDPE	340	300	60	1–3	315	305	300
PG 58-28 + 0.8 % LDPE	340	300	60	3	315	305	300

¹ PG 64-22 designs were tested with 0.2, 0.4, 0.6, and 0.8% LDPE in addition to the 0% LDPE control.

Rutting resistance was evaluated with the Asphalt Pavement Analyzer (APA) following the current AASHTO T340 procedure; each set comprised six cylindrical specimens compacted at $7.0 \pm 0.5\%$ air voids, conditioned at 64°C and submitted at 8,000 cycles of 100 lb loaded wheels over 100 PSI inflated hoses.

As shown in Figure 4, a strong linear relationship was established between rut resistance and percent of rPE. The increased rutting resistance results from the mineral structure reinforcement combined with the greater resistance of the rPE-modified binder to plastic deformation. A parallel relationship was obtained with the PG 58-28 binder. An 0.55% of rPE by weight of dry aggregate allowed the PG 64-22 design to match the PG 70-22M rutting performance, and 0.60% would be required for the PG 58-28 formulation.

Low-Temperature Cracking Susceptibility—Temperature Stress Restrained Specimen Test

The Temperature Stress Restrained Specimen Test (TSRST) AASHTO TP10, measures the tensile stress in a specimen that is cooled at a constant rate of $10^\circ\text{C}/\text{h}$, while being restrained from contracting. TSRST measures the tensile stress and the temperature at which fracture occurs. The test is performed on specimens 60-mm Dia. x 250-mm high, cut from laboratory compacted slabs. TSRST is considered an indicator of low-temperature cracking, correlating with BBR results (3–4). Tests were performed at the ETS in Montréal (5), which limited the number of formulations that could be evaluated (PG 64-22 with 0, 0.55, and 0.8% rPE were tested); results are shown in Table 5 and Figure 5.

The TSRST mix rupture temperature of -22.4°C for the 0% rPE blend matched PG 64-22 Low critical temperature. The dry incorporation of 0.55% rPE in the mixture (from which only 0.275% was assumed to be part of the binder) resulted in the TSRST rupture temperature increasing 3.7°C , from -22.4°C to -18.7°C . An immediate conclusion was that the production trial should use a PG 58-28, to maintain the low critical temperature at the -22°C regional level.

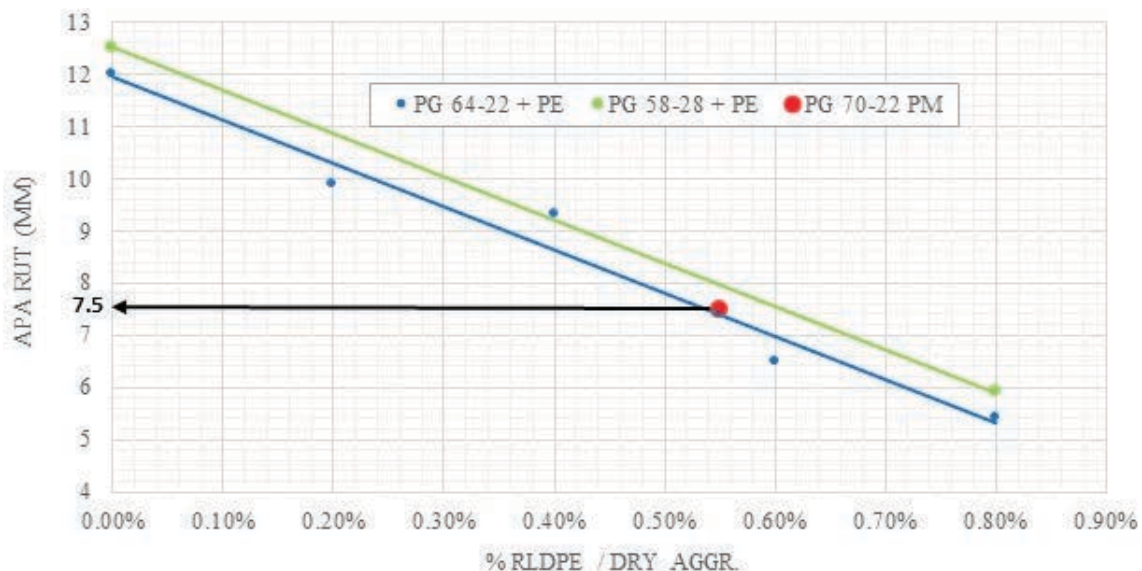
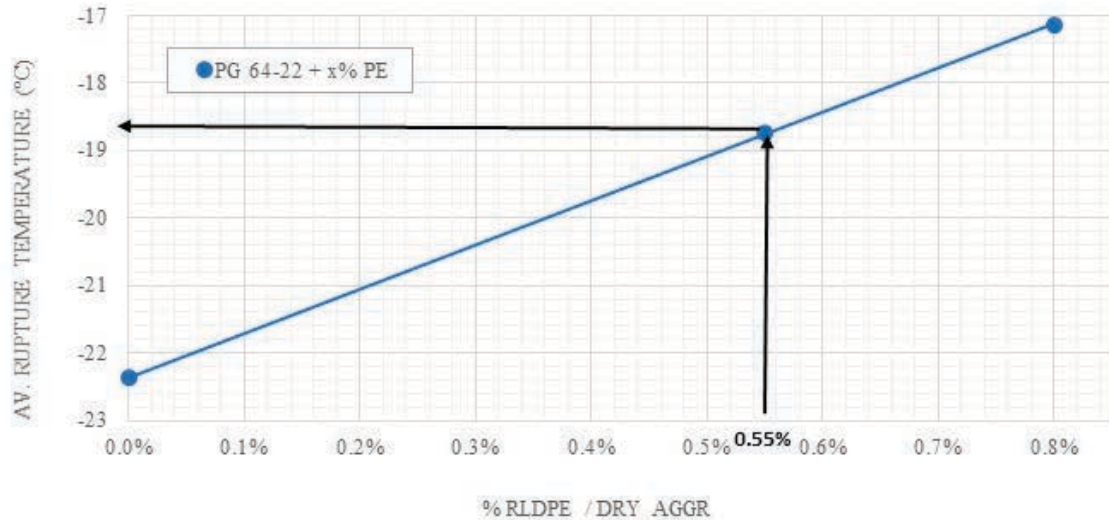


FIGURE 4 Rutting performance–APA evaluation.

**TABLE 5 TSRST Results: Glass Transition Temperature–
Stress and Temperature at Rupture**

PG 64-22 + % Add./Dry Agg.	T _g ¹ °C	Stress @ Rupt. MPa	Temp. @ Rupt. °C
0%	-14.6	2.49	-22.37
rPE			
0.55%	-8.9	2.83	-18.73
0.80%	-6.1	2.60	-17.1

¹ T_g, glass transition temperature at which material's characteristics change from viscoelastic to brittle.

**FIGURE 5 TSRST rupture temperature vs. % additive.**

Binder Performance Evaluation

The PG characteristics of the rPE-binder blends were then evaluated to study the TSRST-BBR correlation. However, the first immediate difficulty encountered was the instability of those blends. The samples had to be constantly agitated before testing and the top of the sample had, at times, to be eliminated prior to performing DSR and BBR testing.

The rPE-binder blend proportions were adjusted to correspond to the ratios used for the laboratory mixture study. The impact of rPE on the rheology of the reference PG 64-22 was evaluated using the DSR (AASHTO T315), the BBR (AASHTO T313), and the direct tension test (AASHTO T314). Separation tendency, penetration, and softening point were also determined. The results for tests performed on the PG 64-22 blends are summarized in Table 6 along with TSRST results. The main findings were as follows:

- The strong stiffening effect of rPE was evidenced by the increases in viscosity, the $G^*/\sin\delta$ parameter, and softening point as well as the decrease in penetration.
- The separation test unequivocally demonstrated the high instability of the rPE-binder blend.
- rPE impact on low-temperature properties was strong; from 0% to 13% of rPE by weight, the binder became totally “m-controlled” meaning $T^{\circ}c_m$ increased almost 12°C from –

24.8° C to –13.1°C, while T°_{cs} did not change; rPE impacted primarily the relaxation performance of the binder.

- From 0% to 8.9% rPE, corresponding to the 0.55% rPE by dry aggregate weight tested with TSRST, T°_{cm} increased 8.3°C, twice the rate observed with the TSRST. As the chart on Figure 6 suggests, BBR (m) and TSRST results were decoupled and DTT and TSRST followed the same trend.
- However, if TSRST results are plotted against half of the percent rPE by weight in the binder (Figure 7), BBR (m) and TSRST results are aligned. This correlation is consistent with the partial blending of rPE and modification of the binder.

TABLE 6 rPE-PG 64-22 Blends–Binder and TSRST Summary Results

Tests		%PE/ Dry Agg.	0%	0.55%	0.8%
		%PE / Binder	0.0%	8.9%	13%
DSR AASHTO T315	T° at G*/sinδ = 1.0 kPa Original Binder	°C	65.4	78.8	101.8
	T° at G*/sinδ = 2.2 kPa RTFO Residue	°C	64.6	76.9	85.2
BBR AASHTO T313	T° at s (60) = 300 MPa RTFO and PAV Residue	°C	–24.8	–24.8	–25.2
	T° at m (60) = 0.300 RTFO and PAV Residue	°C	–24.8	–16.5	–13.1
ΔTc (S-m) 20 h		°C	0.0	–8.3	–12.1
Rotational viscosity original binder AASHTO T316	135°C	Pa.s	0.401	2.245	4.793
	165°C	Pa.s	0.112	0.751	1.247
Penetration Original Binder ASTM D5		dmm	58	26	21
Separation test softening point original binder LC 25-003	Top part	°C	47.1	114.4	114.3
	Bottom part	°C	47.0	61.6	67.1
	Difference	°C	0.1	52.8	47.2
	Mean value	°C	47.0	88.0	90.7
Softening point original binder ASTM D36		°C	46.6	57.9	99.6
Density original binder ASTM D70		g/cm ³	1.027	1.008	1.006
DTT AASHTO T314		°C	–24.0	–22.3	–17.8
TSRST ETS AASHTO TP10		°C	–22.37	–18.73	–17.10

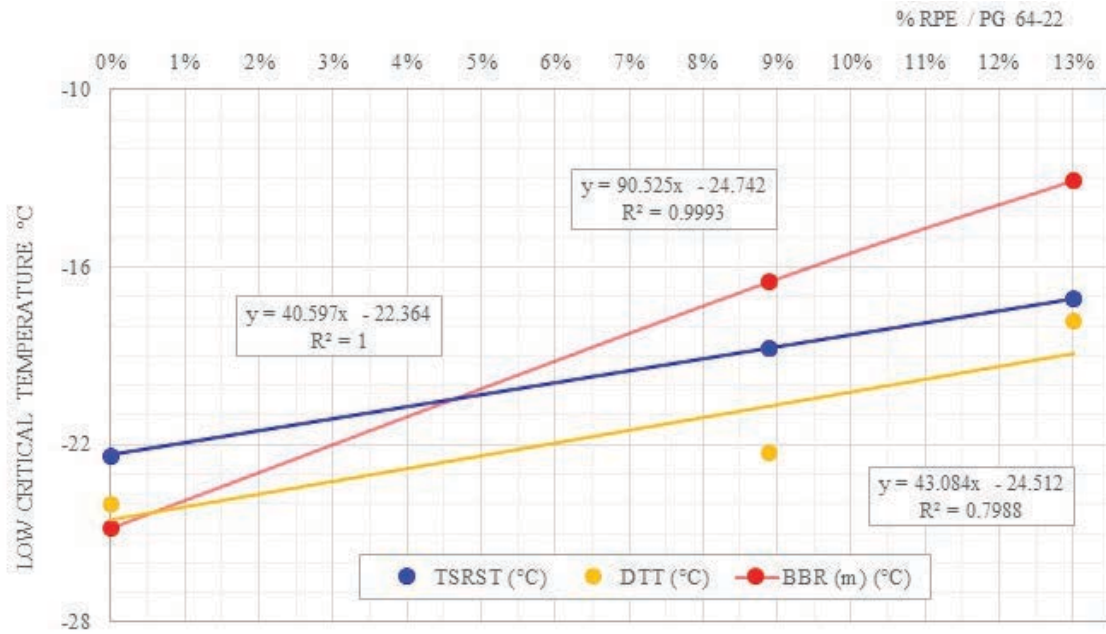


FIGURE 6 Temperatures TSRST-BBR (m)-DTT.

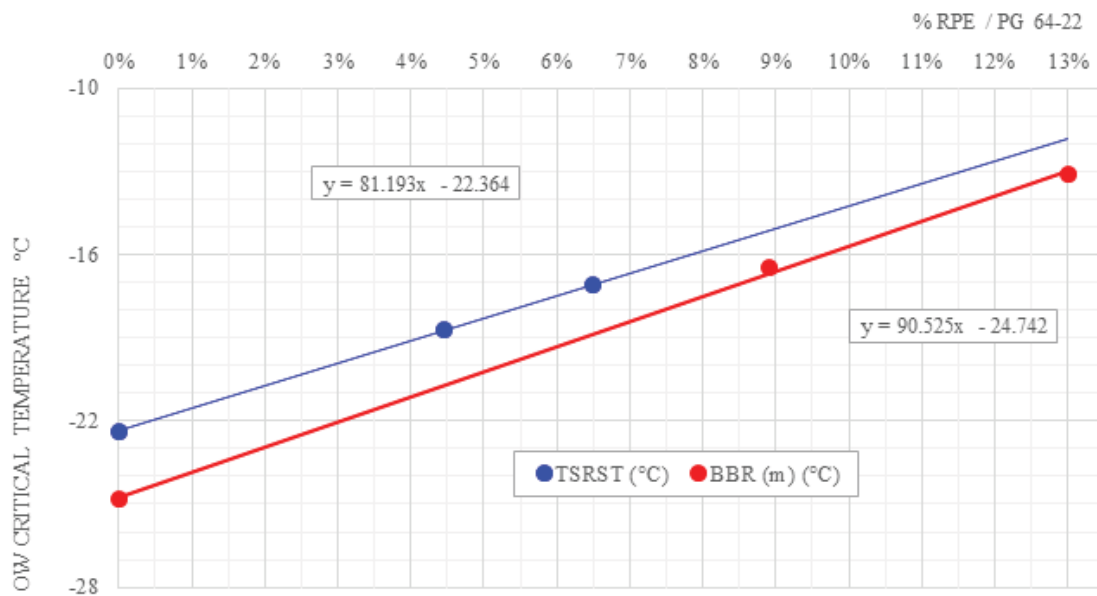


FIGURE 7 Temperatures TSRST (50% rPE in binder)-BBR (m).

Clermont County Road Project, Cincinnati, Ohio

In addition to the laboratory performance evaluation, a production trial took place on a local county road based on project specification Ohio DOT “Type 1” (50 blows Marshall Design).

The two designs in Table 7 were placed side by side; the control mix, produced from a continuous drum mixer, incorporated 20% RAP; the 400 tons of rPE-modified mix was produced from a batch plant that could not incorporate RAP, which was replaced with a #9 / #10 aggregate blend. Considering the findings above, the rPE-modified mix used a PG 58-28 to compensate for the critical low-temperature increase.

Production

The rPE was incorporated manually in the pugmill with pre-weighted meltable bags. Dry mix time was increased by 5 seconds and wet mix time by 10 seconds to allow for a good dispersion and blending of rPE particles. Production temperature was 350°F (177°C).

Paving

The mix was placed in a 2-in. (5-cm) lift and compacted with paver screed vibration on, three passes of a 12.5 tons steel drum vibratory roller (low amplitude, 3200 vpm), completed with a light steel drum static roller. Compaction temperature window was 320°F (160°C) behind the screed down to 270°F (132°C). Ambient temperature was in the 50’s (10°C and above).

Densities and Rutting Performance

Six 6-in. (150-mm) cores were cut in each section to be tested in the APA (Figure 8). Average cores densities were 94.9% Gmm on the rPE section and 94.2% Gmm on the control section.

The rPE-modified cores reached 4-mm rutting where the Marshall control mix rutting was 12-mm. For comparison, the envelope of the APA results performed on the same equipment on various PG 76-22 Superpave 0% RAP formulations was reported on the figure. Albeit the PG

TABLE 7 Clermont County Road Project Mix Designs

50 blows 9.5 mm Marshall Design “Type 1” Ohio DOT			50 blows 9.5 mm Marshall Design rPE-Modified		
%	Size	Type	%	Size	Type
45.0	#8	Crushed Limestone	53.8	#8	Crushed Limestone
15.0	#10	Manufactured Sand	13.9	#9	Crushed Limestone
20.0	#10	Natural sand	15.9	#10	Manufactured Sand
20.0	—	RAP	15.9	#10	Natural sand
—	—	—	0.53	—	rLDPE
100	—	Total Aggregates	100	—	Total Aggregates
5.0	AC	Virgin PG 64-22	5.8	AC	58-28

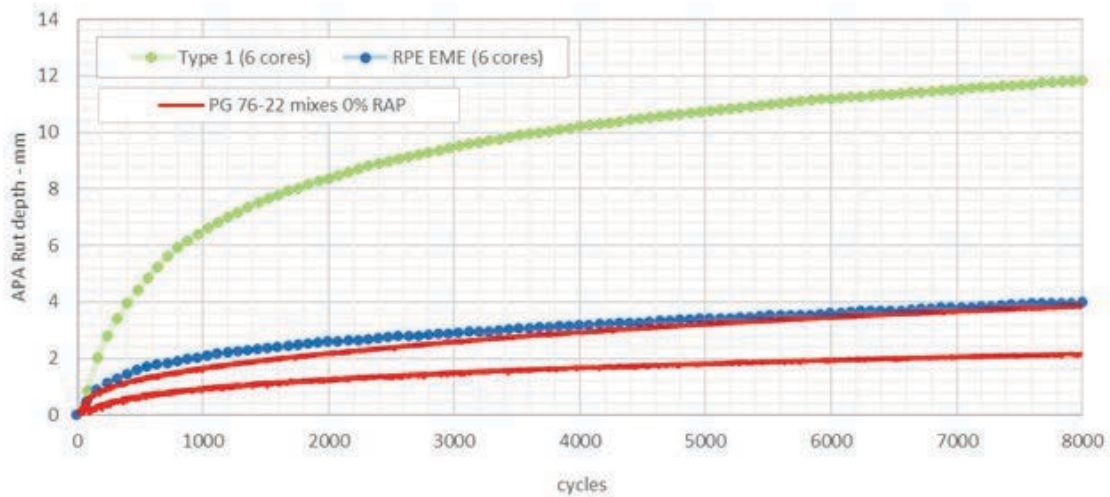


FIGURE 8 APA tests on cores -64°C , 100 psi, 100 lb, 8,000 cycles, comparison to PG 76-22 designs.

76-22 mixes specimens were tested at the standard 7.0% air voids content, the incorporation of half a percent recycled LDPE allowed a PG 58-28 Marshall mix to match the rutting resistance of Superpave PG 76-22 SBS-modified designs.

Economic Evaluation

The economic evaluation done at the time of project established that the costs related to rPE procurement and to binder adjustment to maintain low-temperature performance equated those of a regular polymer-modified binder. At similar performance levels, the rPE-modified mix did not bring any savings.

CONCLUSIONS

- Dry processed rPE Asphalt Mixes have been used in France for nearly 50 years in High Modulus Asphalt Mixes applications. When incorporated as a dry additive, rPE acts as a binder modifier as well as a reinforcement, which explains rPE asphalt mixes' rutting resistance. rPE also contributes to a thicker effective binder film, responsible for good fatigue response, lower water sensitivity and relatively easy compactibility. Last, rPE improves asphalt mixes fuel resistance.
- Practicality and cost-efficiency are key advantages of the dry process, as the dry additive eliminates the need for an additional tank and the costs associated with the rPE-binder blend stabilization. This makes the process particularly attractive for small tonnages.

- Performance evaluation with North American tests methods (APA, TSRST, PG) confirmed the rutting resistance and evidenced the impact on Low-Temperature Cracking resistance.
- The field trial demonstrated that production and placement were straightforward and confirmed the good compactibility and rutting resistance of the rPE-modified mixes.

PERSPECTIVES

As mentioned, collecting and sorting plastics has a cost that cannot be offset by material replacement in a low-bid market. Looking at performance, rPE-modified mixes rutting resistance make them competitive with polymer-modified binders mixtures in certain applications; however, satisfying to low-temperature cracking requirements, does not make them more cost-efficient.

This means that for a successful development and giving a second useful life to polymers instead of landfilling them, the full environmental benefits of recycling plastics must be accounted for, based on life cycle analysis.

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Commercially Available Recycled Plastic Products for the Modification and Extension of Asphalt Binder

A Case Study on MR6 and MR10

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The desire to develop more sustainable infrastructure, including pavement structures and materials, is ever increasing. Using recycled plastics in asphalt concrete has gained significant attention in recent years, despite having been trialed and offered by various companies since the 1980s. Although some solutions are as simple as shredding up milk containers, bottles or crates and adding them to the asphalt concrete production plant, MR6 and MR10 are commercially available recycled plastic products that have been produced under a quality assurance system since 2016. These products have been tested using various asphalt binder and mixture tests commonly specified in the United Kingdom, the United States and Australia. Comparisons to unmodified asphalt binders were performed using a range of dense graded and stone mastic asphalt concrete mixtures, as well as various grades and unmodified asphalt binder. MR6 and MR10 generally increased the resistance of asphalt binder to flow and the resistance of the asphalt concrete mixtures to deformation. Significant asphalt binder ductility and elasticity was introduced, but the effect on asphalt concrete crack resistance was either moderate or not significant. There was no significant change to asphalt concrete moisture damage resistance, but the stiffness of various asphalt concrete mixtures increased two- to three-fold. Overall, the general effects of MR6 and MR10 were found to be similar to the effects associated with conventional polymer modification of asphalt binders and asphalt concrete mixtures, particularly those associated with the plastomeric polymer EVA.

INTRODUCTION

The desire to develop sustainable infrastructure, including pavement structures and materials, is ever increasing in recent times (1). Given the diversity of pavement structures, which can include cement concrete, asphalt concrete, granular crushed rock and natural gravels, the opportunities for sustainable pavement construction are broad and many. When considering sustainability opportunities, it is important to take into account the effect on the durability and expected life of the pavement, as well as the reduction in financial or environmental cost of the more sustainable solution (2). That is, an initiative that reduced the new pavement's greenhouse gas emissions by 20% is not sustainable if the pavement only lasts 50% of the life of the conventional solution (3). It is also important to understand that sustainability initiatives are only viable if the cost to collect, process and reincorporate a recycled material or product is less expensive than the cost of the material or product that it replaces (4). For this reason, the

replacement of high-cost materials, such as asphalt binder and cement, with recycled or repurposed materials, is a great interest.

The replacement of the asphalt binder and aggregate in asphalt concrete mixtures, with recycled waste or repurposed by-product, is very attractive and has gained much attention in recent years. In addition to the well-established recycling of reclaimed (milled) asphalt concrete, the extension of fine aggregate with crushed glass, partial replacement of aggregate with blast furnace slag, extension, or modification of asphalt binder with crumbed tire rubber and the extension or modification of asphalt binder with plastic, are all viable solutions in asphalt concrete pavements and surfaces. The replacement materials are all high-profile wastes from other industries and the material being replaced is a relatively expensive element within any pavement structure.

Recycled plastic in asphalt concrete has gained significant attention in recent years, despite having been trialed and offered by various companies since the 1980s (5). Some solutions are as simple as shredding up milk containers, bottles or crates and adding them to the asphalt production plant (6). In contrast, some researchers have depolymerized waste plastic and recycled the raw polymers (7). The former of these approaches is unlikely to produce consistent results, while the latter is unlikely to be practically viable on a cost-effective scale. As a result, the most viable approaches to recycled waste plastic in asphalt concrete mixtures are:

- Proprietary mixtures. Where a supplier provides the finished asphalt concrete mixture containing plastic.
- Proprietary additives. Where a supplier provides a modified binder or plastic pellets/crums that can be added to asphalt binder or the asphalt concrete mixture by any producer.

Regardless of the approach taken, the great diversity in recycling approaches, plastic types, plastic contents, and the interaction with other additives creates a significant challenge for the procurement of asphalt concrete mixtures containing recycled plastic as a sustainable pavement solution. This puts the onus on the producer/supplier of any given recycled plastic modifier or modified asphalt concrete mixture, to demonstrate the performance and acceptability of their product. It also requires that the producer/supplier maintains a transparent quality assurance system to provide confidence that the product supplied on any given day is comparable to the product on which the performance demonstration was made.

This paper presents a case study on two commercially available recycled plastic products for the modification and extension of asphalt binders in asphalt concrete mixture production. The products, known as MR6 and MR10, are intended to be plastomeric and elastomeric, respectively. This case study is focused on the physical and mechanical properties of asphalt binder and asphalt mixtures produced with both products. Environmental and practical issues, such as leaching, fuming and storage stability, are not addressed here.

The data presented in this case study is largely extracted from existing publications on the effects of MR6 and MR10 on asphalt binder and asphalt concrete mixture properties. The applicable publications are summarized in Table 1. In all cases, the recycled plastic was added at a rate of 6% of the asphalt binder mass.

TABLE 1 MR6 and MR10 Research Publications

Title	Focus and Scope	Year	Reference
Recycled Waste Plastic for Extending and Modifying Asphalt Binders	Summary of the products and the effect on asphalt concrete performance properties.	2018	(8)
Evaluating Recycled Waste Plastic Modification and Extension of Bituminous Binder for Asphalt	The effect on typical asphalt concrete performance properties, as well as environmental and safety issues.	2019	(9)
Recycled Waste Plastic Modification of Bituminous Binder	The effect on the PG rating of two penetration grade asphalt binders.	2019	(10)
Objective Evaluation of the Practical Benefits of Asphalt Binders Modified With Recycled Plastic	The improvement in base and surface mixture modulus and fatigue life and the associated effect on predicted pavement life.	2019	(11)
Laboratory Evaluation of Asphalt Containing Recycled Plastic as a Bitumen Extender and Modifier	Effect of common asphalt binder properties and surface mixture performance properties.	2019	(12)
Recycled Plastic as an Alternate To Conventional Polymers for Bituminous Binder	Summary of the effects on various asphalt binder properties, including those used in the United Kingdom (UK), Australia and the United States.	2020	(13)
Laboratory Comparison of Wet-Mixing and Dry-Mixing of Recycled Waste Plastic for Binder and Asphalt Modification	Comparison of the effect of production process on the asphalt binder and mixture properties of a common surface mixture.	2021	(14)

PRODUCTS

Both MR6 and MR10 were developed and are produced by MacRebur Ltd (15). In 2015, MR6 was developed to:

- Productively consume a portion of the waste plastic otherwise destined for landfill.
- Reduce the cost of new road construction and maintenance.
- Increase the strength and durability of local roads.

MR6 was developed to improve deformation resistance via an increase in asphalt concrete stiffness. Two other products, known as MR8 and MR10, soon followed with different target applications. MR8 was developed as an economical asphalt binder extender while MR10 was developed to produce an elastomeric and crack resistant asphalt binder. All products are manufactured from 100% recycled plastic that was selected for its physical properties, as well as being otherwise not economically recyclable. That is, the plastic used to produce MR6, MR8 and MR10 would otherwise be disposed in landfill because there are no viable alternate recycling opportunities at this time.

The original MR6, was developed in a pelletized form. This included melting, extruding, and cutting of the recycled plastic. This produced dense pellets with homogenous color (Figure 1). The density of the pellets was determined to optimize the international shipping costs, which are

based on the worse case of product volume and weight. By adjusting the packed density, the volume-based and weight-based shipping costs were equal, which is the most efficient for shipping. MR10 was also developed as a pellet, but MR8 was developed as a flake (Figure 1). However, to improve the distribution of MR6 and MR8 through the asphalt concrete mixture when a dry-mixing process is used, both were converted to a shredded form in 2019. Due to the different chemical composition of MR10, it is still produced in a pelletized form (Figure 2).

Despite MacRebur being located in the United Kingdom (UK), MR6, MR8 and MR10 have now been used on every habitable continent in the world. The combined quantity of MR6, MR8 and MR10 delivered globally increased from 2016 to 2020 (as seen in Table 2 and the most recent data available when this circular was written). At the recommended dosage of 6% of the asphalt binder mass, and a typical 5% binder content in asphalt concrete mixtures, the total 1,440 tons of recycled plastic product supplied since 2016 is equivalent to approximately 480,000 tons of asphalt concrete containing MR6, MR8 or MR10.

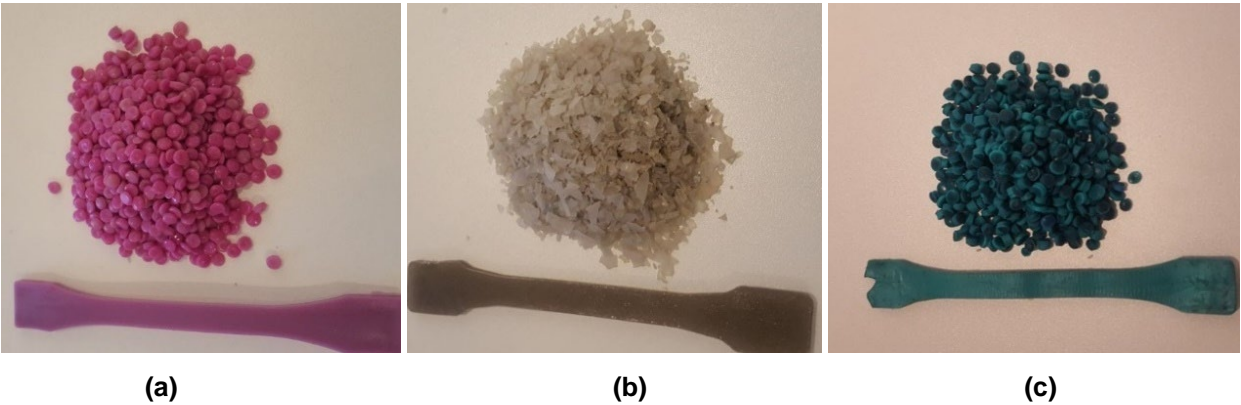


FIGURE 1 Original (a) MR6 pellets, (b) MR8 flakes, and (c) MR10 pellets.

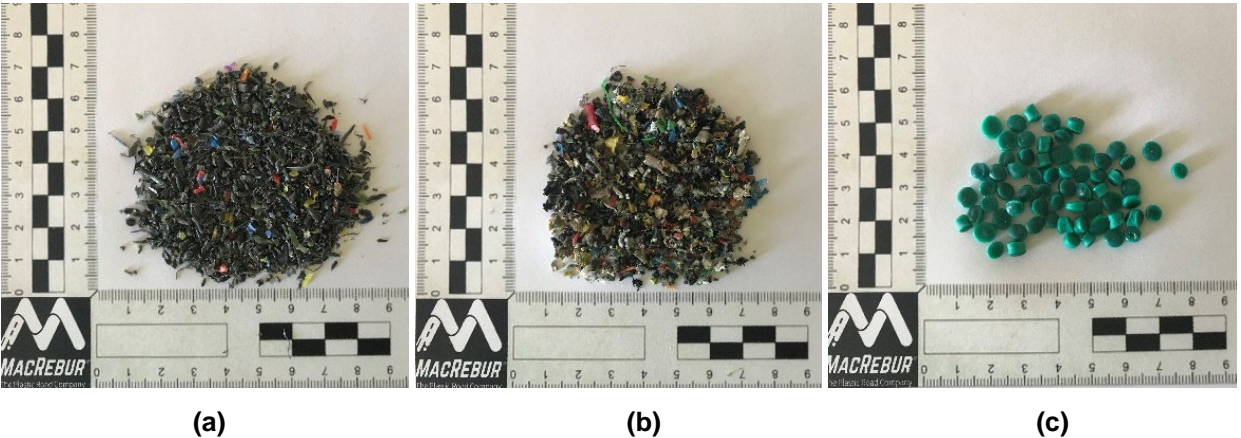


FIGURE 2 Current (a) MR6 shavings, (b) MR8 shavings, and (c) MR10 (unchanged).

TABLE 2 Tons of Total MR6, MR8 or MR10 Shipped by Year

Year	Country							
	United Kingdom	United States	Middle East	Europe	Asia	Africa	Australasia	Total
2016	20 T							20 T
2017	80 T							80 T
2018	180 T		10 T	20 T			20 T	230 T
2019	250 T	20 T	20 T	40 T		20 T	60 T	410 T
2020 (to July)	180 T	180 T	40 T	80 T	140 T	20 T	60 T	700 T
Total	710 T	200 T	70 T	140 T	140 T	40 T	140 T	1,440 T

This paper is focused on MR6 and MR10, which reflects the intent of MR8 being as an asphalt binder extender without providing any improvement in the physical properties of the asphalt binder or the mechanical properties of the asphalt mixture. However, some MR8 results are included where they are available.

EFFECTS ON ASPHALT BINDER

Different jurisdictions use different test methods to measure the physical properties of asphalt binders. In many countries, the specified and commonly tested asphalt binder properties are relatively simple in nature, often referred to as index tests, such as softening point, viscosity, penetration, as well as indicators of stiffness and ductility or elasticity (16). However, in the USA, DSR parameters are routinely tested under the PG system (17).

Table 3 summarizes index testing performed on samples with and without recycled plastic in Australia and the UK. Penetration and viscosity 60 are general indicators of stiffness or resistance to deformation, which elastic recovery, force ductility and torsional recovery are indicators of elasticity. The softening point is a measure of the temperature at which the asphalt binder transitions from being predominantly solid to predominantly liquid, which is an indicator of temperature susceptibility.

Resistance to Flow

Viscosity 60 measures flow potential and penetration measures the resistance to flow. Generally, penetration and viscosity are inverse, in that as viscosity increases, penetration decreases for the same asphalt binder. The penetration of 100-150 penetration grade asphalt sourced and tested in the UK reduced by 33% and 30%, with the addition of MR6 and MR10, respectively (Figure 3). The additional of MR8 was associated with a slight increase in the penetration, reflecting the non-performance-enhancing nature of MR8. Similarly, for 70–100 penetration bitumen, MR6 and MR10 reduced the penetration by 54% and 36%, respectively (Figure 4). Accelerated laboratory aging by the rolling thin film over (RTFO) reduced the

TABLE 3 Asphalt Binder Test Methods

Property	Method	Description	Measured in Research
Penetration	EN 1426	Penetration by a standard needle, over 5 s, into an asphalt binder sample at 25°C	(10, 14)
Force ductility	EN 13703	Percentage of elongation until separation of an asphalt binder sample at 25°C	(10)
Elastic recovery	EN 13398	Percentage recovery of a cut asphalt binder sample after elongation by 200 mm at 25°C	(14)
Softening point	EN 1427 (UK) and AG:PT/T131 (A)	Softening temperature of an asphalt binder sample according to the R&B method	(10, 12, 14)
Viscosity 60	AS 2341.2	Propensity of the asphalt binder to flow under load at 60°C	(12)
Torsional recovery	AG:PT/T122	Percentage of torsional recovery of an asphalt binder sample after rotating 180° at 25°C	(12)

Note: (UK) denotes the method used in the UK while (A) denotes the test method used in Australia.

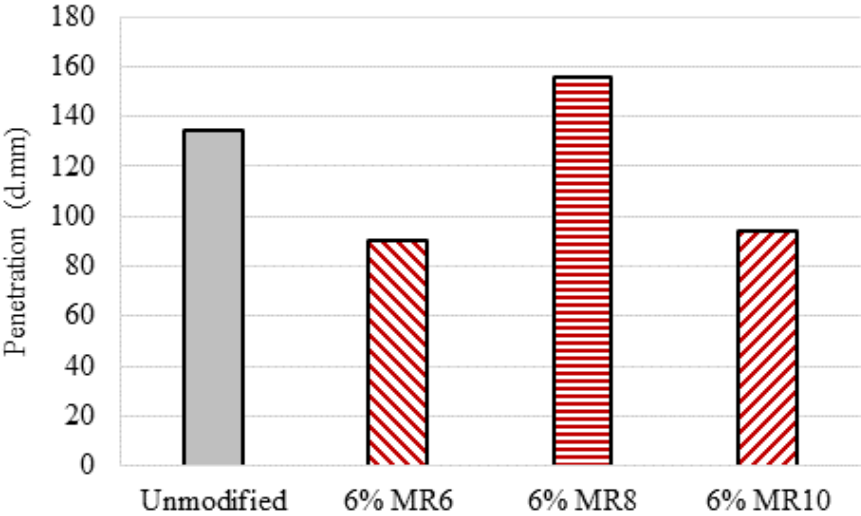


FIGURE 3 Effect of recycled plastic on 100–150 bitumen penetration (10).

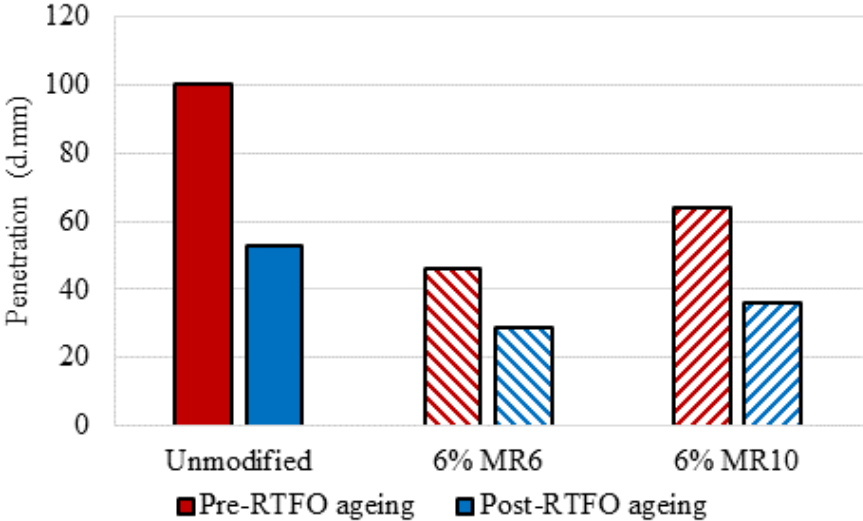


FIGURE 4 Recycled plastic effects on unaged and aged 70–100 bitumen penetration (14).

unmodified asphalt penetration from 100 d.mm to 53 d.mm and the penetration of the MR6 and MR100 modified samples was 45% and 32% of the unmodified asphalt penetration after RTFO (Figure 4). The reduced relative penetration after RTFO aging indicates that the additional of recycled plastic may also slow the asphalt binder aging process. However, research would be needed to confirm this. Finally, the viscosity of Australian C170 (viscosity grade) asphalt increased by 113% for MR6 and by 164% for MR10 (Figure 5). MR8 increased the viscosity by 87%.

All these results indicate the addition of recycled plastic to otherwise unmodified asphalt increases the stiffness and resistance to flow of the asphalt binder. This is similar to the effect observed when conventional SBS and EVA polymers are added to asphalt at comparable dosages.

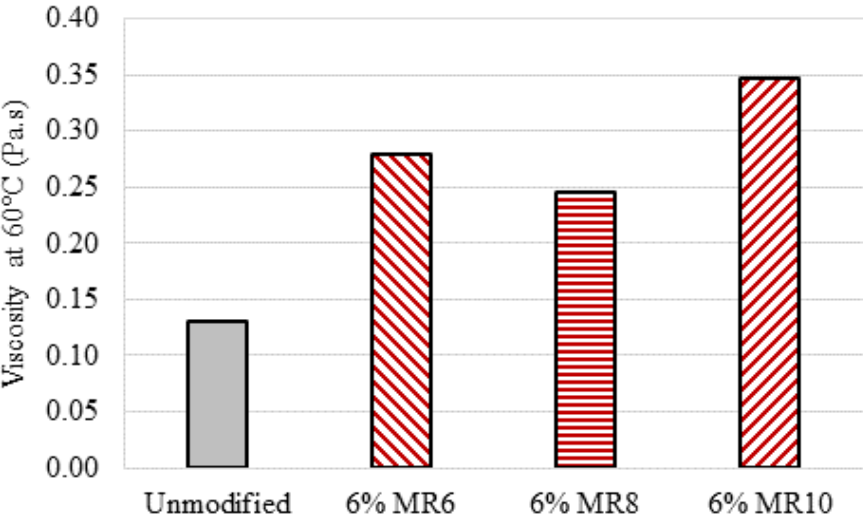


FIGURE 5 Effect of recycled plastic on C320 viscosity (12).

Elasticity and Ductility

Force ductility measures the degree of elongation before an asphalt binder sample is broken. Both torsional recovery and elastic recovery measure the degree to which a sample recovers after deforming, either by rotation or by elongation. Unmodified 100–150 penetration asphalt and C320 viscosity grade asphalt have negligible elasticity or ductility. However, when recycled plastic is added, the force ductility (Figure 6), elastic recovery (Figure 7) and torsional recovery (Figure 8) all increased significantly. MR10 had a greater effect on the elasticity and ductility of the asphalt than MR6 did, while MR8 had the least effect. The introduction of significant ductility and elasticity is consistent with the effect of moderate SBS or significant EVA conventional polymer modification of asphalt binder.

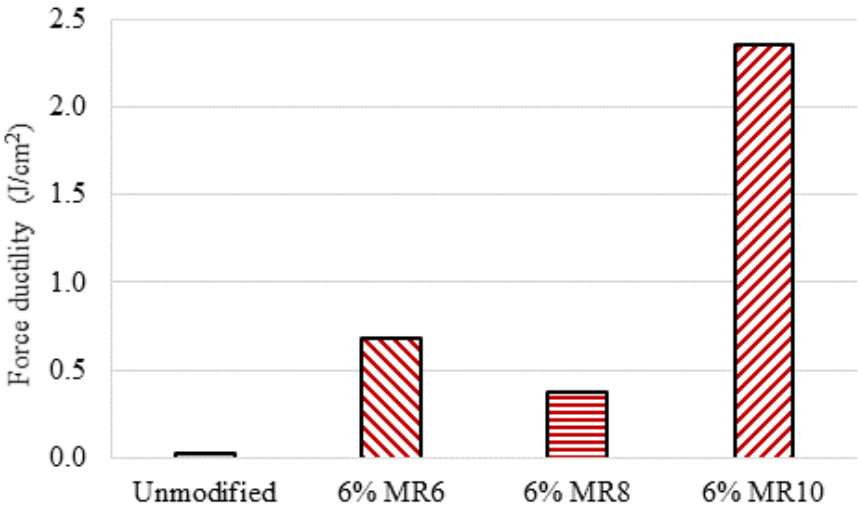


FIGURE 6 Effect of recycled plastic on 100–150 bitumen force ductility (10).

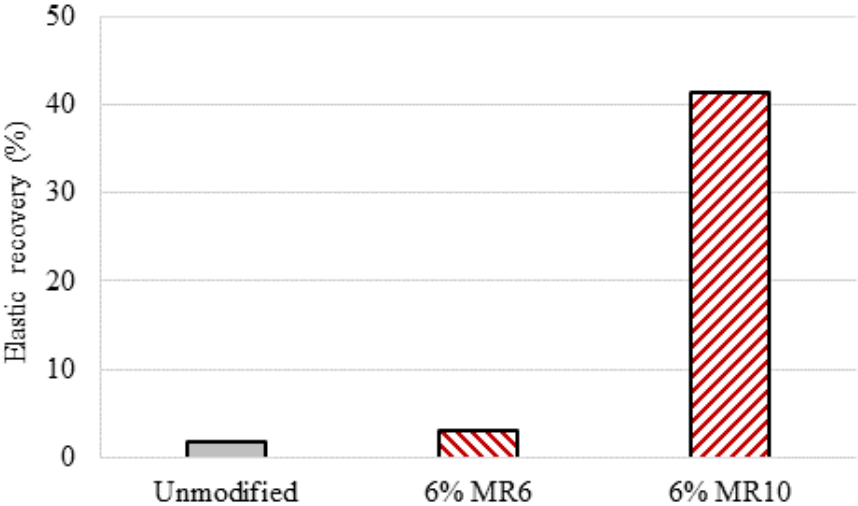


FIGURE 7 Effect of recycled plastic on 70–100 bitumen elastic recovery (14).

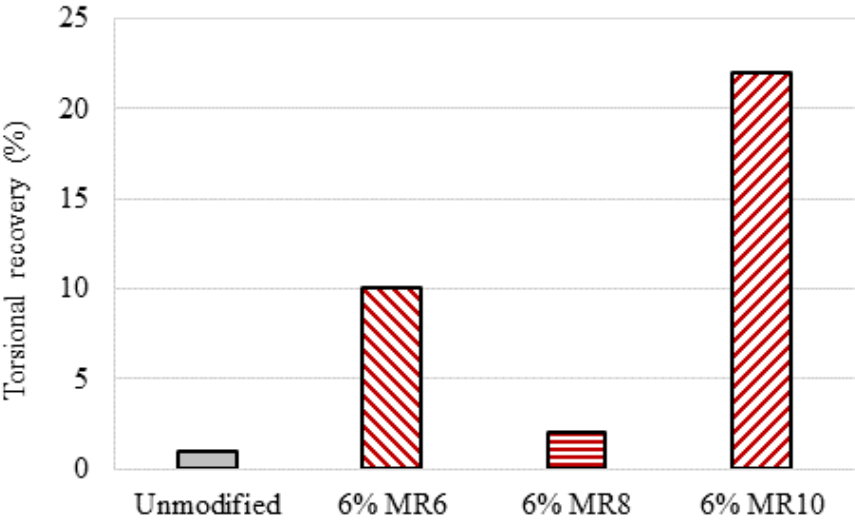


FIGURE 8 Effect of recycled plastic on C320 torsional recovery (12).

Temperature Susceptibility

Softening point is globally recognized as an index property for temperature susceptibility of PMA binders. In general, an asphalt binder with a higher penetration will have a lower softening point. When recycled plastic was added to 100-150 penetration grade asphalt in the UK, the softening point increased by 22% (MR6) and 14% (MR10) (10). MR8 was associated with a slight decrease in softening point, by 3%. For Australian C320 asphalt, the softening point increased by 45% and 32%, for MR6 and MR10, respectively (12). Similarly, MR8 was associated with a smaller change, just a 9% increase in softening point. Finally, the softening point of 70–100 penetration binder increased by 40% and 20%, with the additional of MR6 and MR10, respectively (14). The RTFO aging of the asphalt increased the softening point by 16%, reflecting the oxidative hardening of the asphalt. After RTFO, the effect of recycled plastic was reduced, with a 27% and 22% increase associated with MR6 and MR10, respectively.

Because the softening point test protocol is almost identical in Australia and the UK, the average effect can be examined by combining the various data sets (Figure 9). Overall, the additional of MR6 increased the asphalt binder softening point by 33%, while the addition of MR10 increased the softening point by an average 23% and the effects were significant (p-values 0.01 and 0.02, respectively).

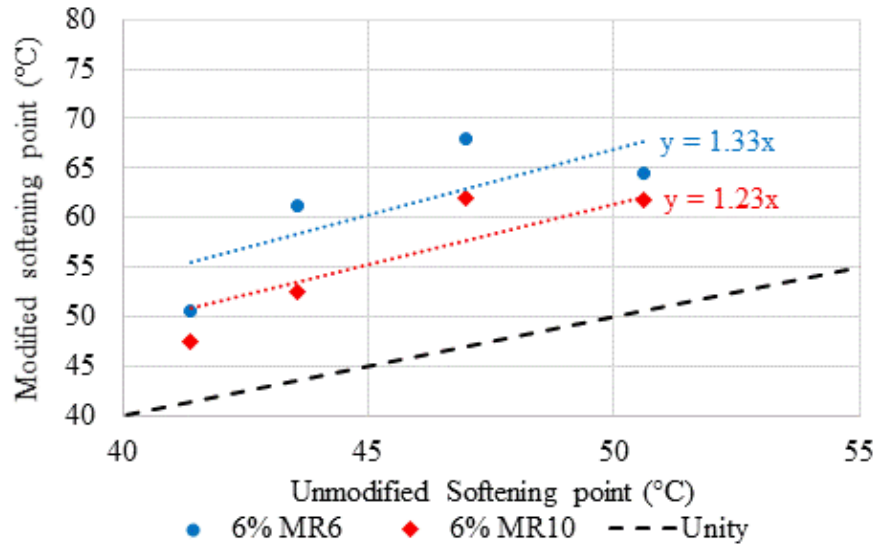


FIGURE 9 Effect of recycled plastic on binder softening point (10, 12, 14).

Performance Grading

The PG rating and specification of asphalt binders in the USA was one result of the Superpave project conducted in the 1990s (18). Although there are also low-temperature parameters, the primary parameter of interest in the high-temperature limit. The original PG grading was based on the DSR parameter known as $G^*/\sin(d)$. However, since 2011, the DSR protocol known as the MSCR test has been used to determine the parameter known as $J_{nr(3,2)}$, which is now the primary basis of high-temperature PG rating (19).

Both a 100-150 and a 50-70 penetration grade asphalt from the UK were modified with MR6 and MR10. Both MR6 and MR10 increased the PG of both asphalts significantly (Figure 10). On average, MR6 was associated with four grade increases while MR10 was associated with an average three grade increases (Figure 11). Three to four PG rating increases under the MSCR-based PG system is comparable to the effect of conventional SBS and EVA polymers for asphalt binder modification.

EFFECTS ON ASPHALT MIXTURES

Common test methods for asphalt concrete mixtures are more directly relatable to field performance than the asphalt binder tests. The common test methods are generally intended to be indicators of stiffness, deformation resistance, cracking resistance and moisture damage resistance. Although less directly related to performance, the Marshall properties (20) are still commonly reported in many countries and the Marshall Stability is generally accepted as an indicator of the relative contribution of the asphalt binder to the stiffness of the asphalt concrete mixture, while the Marshall Flow is generally accepted as an indicator of the relative contribution by the asphalt binder to the elasticity or resistance to cracking of the asphalt concrete mixture.

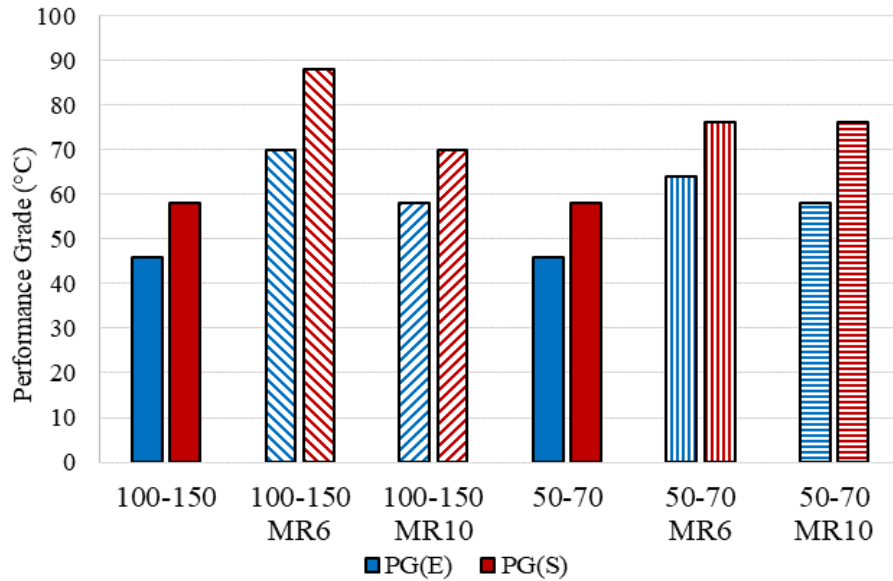


FIGURE 10 Effect of recycled plastic on binder MSCR PG rating (10).

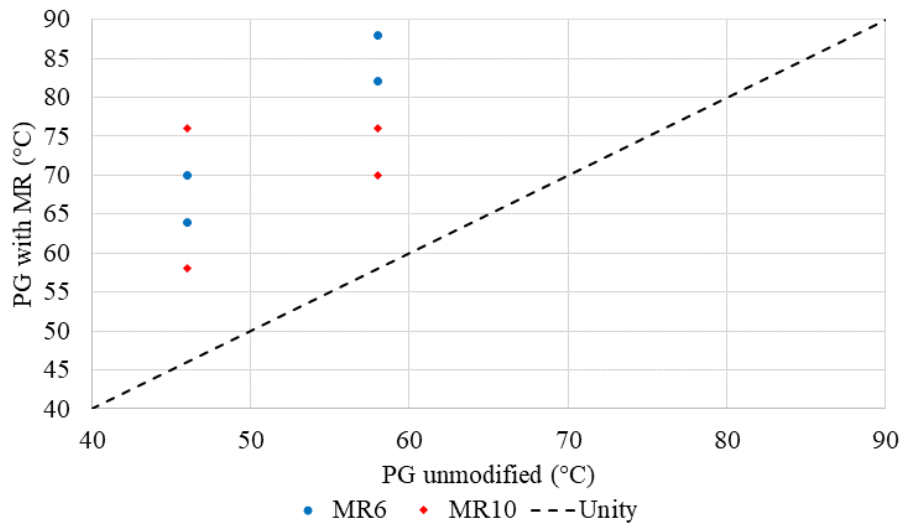


FIGURE 11 PG increase for RPM binders (10).

In some cases, different jurisdictions have their own protocols for what is fundamentally the same test method. The various test methods used by the various research studies to determine the effect of MR6 and MR10 on asphalt concrete mixture properties are detailed in Table 4.

Various studies have used different asphalt mixtures as the basis of the comparison of samples with and without the recycled plastic modifiers. The type of mixture, nominal maximum aggregate size and binder content are detailed in Table 5.

TABLE 4 Asphalt Test Methods

Property	Method	Description	Measured in Research
Stiffness	EN 12697-26 (UK) AS 2891.13.1 (A)	Indirect tensile modulus at 20°C (UK) or 25°C (A), an indicator of sample stiffness	(9, 11, 12)
Stiffness	EN 12697-34 (UK) AS/NZS 2891.5 (A)	Marshall Stability of samples prepared by 50 blows to each side by a standard Marshall hammer and tested at 60°C	(12, 14)
Deformation resistance	EN 12697-22 (UK) AG:PT/T231 (A)	Deformation following 10,000 passes of a Cooper's wheel tracking wheel of samples at a pre-determined temperature, generally 40°C–60°C	(8, 9, 12, 14)
Cracking resistance	EN 12697-24	Indirect tensile fatigue life of over a range of initial tensile strain magnitudes to develop a relationship between initial strain and cycles to failure, an indicator of sample fatigue life	(9, 11, 14)
Cracking resistance	AG:PT/T274	Four-point bending at 20°C and 200 µε sinusoidal repeated load, an indicator of sample fatigue life	(12)
Cracking resistance	EN 12697-44	Semicircular bending of a notched samples under monotonic loading and tested at 0°C, an indicator of sample fracture toughness	(8, 9)
Cracking resistance	EN 12697-34 (UK) AS/NZS 2891.5 (A)	Marshall Flow of samples prepared by 50 blows to each side by a standard Marshall hammer and tested at 60°C	(12, 14)
Moisture damage resistance	EN 12697-12 (UK) AG:PT/T232 (A)	Ratio of indirect tensile strength of conditioned and unconditioned samples, where conditioning includes saturation and 72 h in 40°C water	(8, 9, 12, 14)

Note: (UK) denotes the method used in the UK while (A) denotes the test method used in Australia.

TABLE 5 Asphalt Mixture Properties

Property	Used by Research References			
	(8, 11)	(8, 9, 11)	(12)	(14)
Mixture type	Dense graded	Stone mastic	Dense graded	Dense graded
Mixture size (mm)	20	10	10	10
Binder content (%)	4.8	6.3	4.9	5.2
Standard	EN 13108-1	EN 13108-5	BCC Type 3	EN 13108-1

Stiffness

The stiffness, or modulus, of asphalt concrete mixtures is used as a relative indicator of the structural contribution of the layer to the strength of the pavement. Modulus is the only parameter routinely measured on asphalt concrete that is directly related to pavement thickness design. The stiffer the asphalt concrete, the stronger the pavement will be, or the thinner the pavement can be without compromising its load carrying ability. Although not a direct measure of the stiffness, the Marshall Stability is generally accepted as an indicator of the asphalt binder’s contribution to asphalt concrete mixture stiffness, when the composition of the asphalt concrete mixture is otherwise kept constant.

A typical UK dense graded asphalt concrete (DGA) with nominal maximum aggregate size (NMAS) of 20 mm, referred to as DGA 20, was produced with and without RPM asphalt binder (8). In the same research, a stone mastic asphalt concrete (SMA) with a 10-mm NMAS, referred to as SMA 10, was produced with and without RPM asphalt binder. In both cases, the base asphalt was typical UK 40–60 penetration grade. The MR6 increased the DGA 20 modulus by 48%, whereas the SMA 10 modulus increased by 198% (for MR6), 121% (for MR8) and 254% (for MR10) as shown in Figure 12.

In related work, a comparison of wet-mixing and dry-mixing of recycled plastic in otherwise nominally identical 10 mm NMAS DGA in the UK, referred to as DGA 10, significantly increased the Marshall Stability for the RPM asphalt concrete (Figure 13). The stiffness increase was 80% to 83% (for MR6) and 110% to 161% (for MR10) and the effect of the recycled plastic (plastic modified versus unmodified 50-70) and recycled plastic type (MR6 versus MR10) were more significant than the effect of the production process (wet-mixing versus dry-mixing).

In similar work using a typical DGA road surface mixture produced to Australian specifications, referred to as DGA 10, the effect of RPM asphalt binder was compared to unmodified viscosity grade (C320) asphalt with draduplicate samples. The

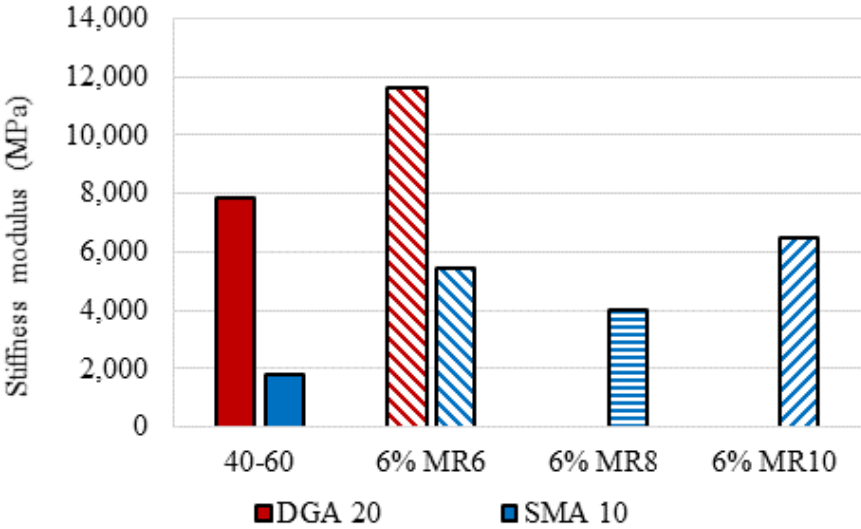


FIGURE 12 Stiffness modulus increase for UK DGA 20 and SMA 10 (8).

recycled plastic increased the asphalt concrete resilient modulus by 12% (for MR6) and 8% (for MR10), as shown in Figure 14. The increase in stiffness was significant, with p-values of 0.01 and <0.01, for MR6 and MR10, respectively. In the same work, the RPM asphalt binder produced mixtures with a 32% (MR6) and 8% (MR10) higher Marshall Stability, compared to unmodified C320 asphalt (Figure 15). Again, the increase was significant, with p-values <0.01 and 0.04, for MR6 and MR10, respectively.

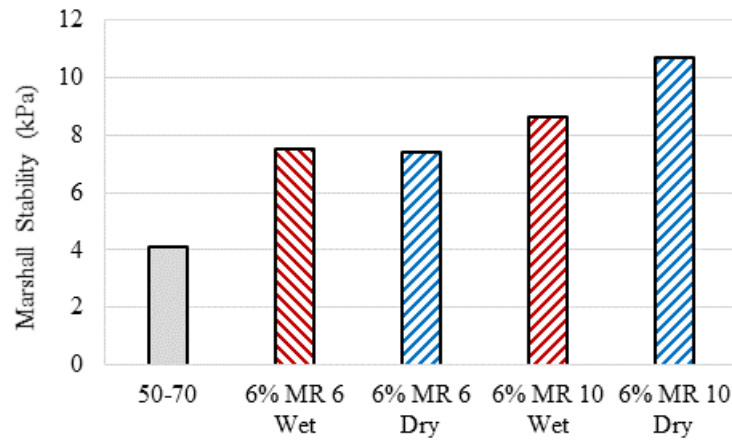


FIGURE 13 Marshall Stability increase for UK DGA 10 (14).

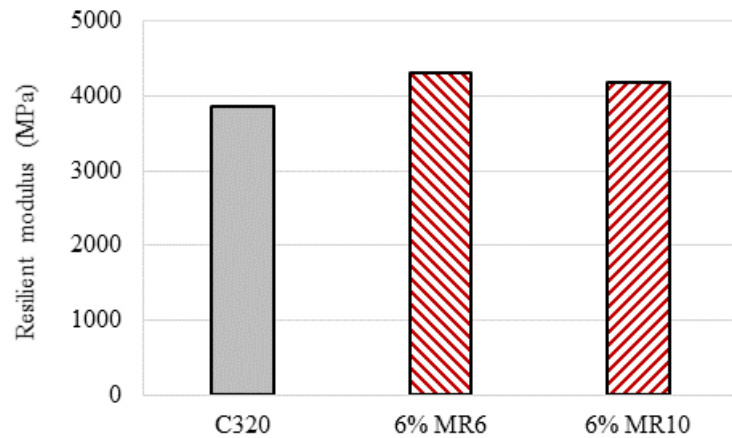


FIGURE 14 Resilient modulus increase for Australian DGA 10 (12).

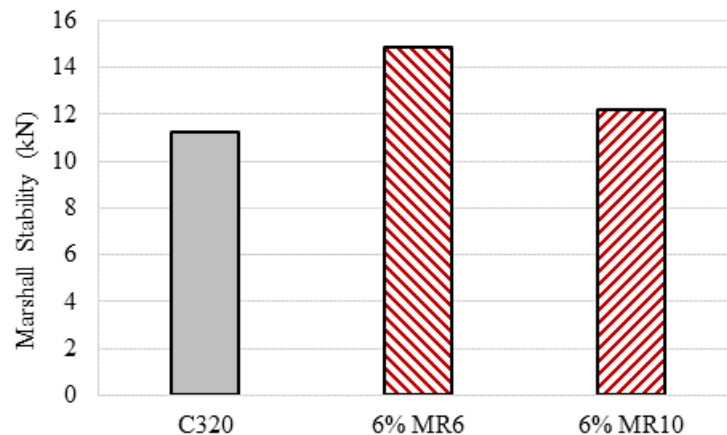


FIGURE 15 Marshall Stability increase for Australian DGA 10 (12).

The results of SMA and DGA asphalt concrete testing, for samples produced with unmodified asphalt and asphalt binder modified with recycled plastic, generally indicate a consistent and significant increase in the stiffness associated with MR6 and MR10 recycled plastic. This is consistent with the effect of conventional polymer modification, particularly for the plastomeric polymer EVA.

Deformation Resistance

Deformation resistance is measured in the UK and Australia using the Copper's wheel tracking machine and is a well-established indirect measure of asphalt concrete mixture resistance to rutting, shoving, and shearing. Other countries, such as the USA, use different wheel tracking equipment or more fundamental deformation resistance tests, such as Flow Number.

The Copper's wheel tracking test was performed on otherwise nominally identical asphalt concrete mixtures produced with and without RPM binders in both the UK and Australia. This included UK DGA 20 and SMA 10 (8), UK DGA 10 (14) and Australian DGA 10 (12). In all cases, the recycled plastic content was 6%, and in all cases the RPM mixtures were compared to otherwise identical mixtures produced with penetration and viscosity grade unmodified asphalt. On average, MR6 was associated with a 65% reduction in the final wheel tracking depth, whereas MR10 was associated with a 43% reduction (Figure 16). The average reduction was statistically significant for both recycled plastic products (p -values < 0.01). This significant increase in asphalt concrete deformation resistance is comparable to that associated with conventional polymers for asphalt binder modification, such as SBS and EVA.

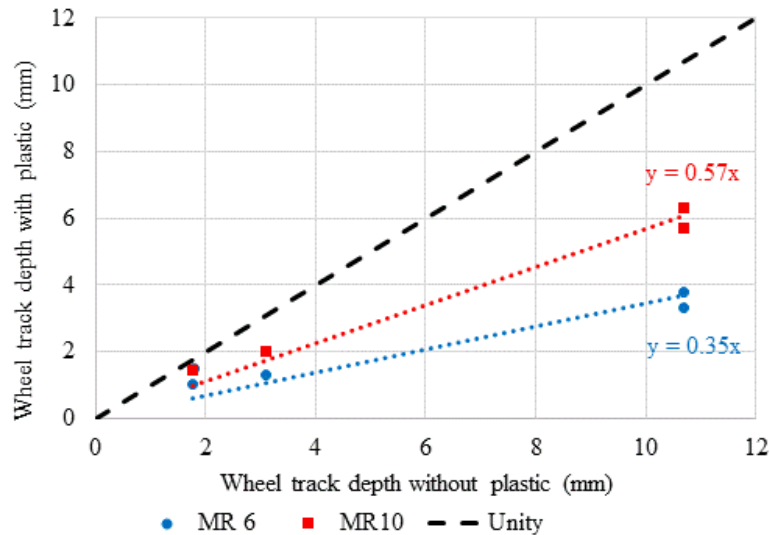


FIGURE 16 Effect of recycled plastic on mixture wheel tracking depth (8, 12, 14).

Cracking Resistance

Cracking resistance is a combination of the resistance to crack initiation (fatigue resistance) as well as resistance to subsequent crack propagation (fracture resistance). There are many laboratory tests for asphalt concrete resistance to cracking, with fatigue tests usually using a cyclic load of a regular sample, while fracture tests usually use monotonic loading of a sample with a pre-made notch or crack initiation point. Although not a direct measure of fatigue of fracture resistance, the Marshall Flow test is generally accepted as an indicator of the asphalt binder's relative contribution to the crack resistance of an asphalt concrete mixture.

The fracture toughness of a typical UK SMA 10 was measured for otherwise nominally identical mixtures, with and without RPM asphalt binder (8). The fracture toughness increased by 22% (for MR6), 8% (for MR8) and 16% (for MR10), as shown in Figure 17. In similar work (9) mixture-specific fatigue life relationships were developed for the same nominal SMA 10 mixture, produced with and without recycled plastic, as well as for a typical UK DGA 20 mixture (11). Over a practical range of induced strain magnitudes (100-500 $\mu\epsilon$), the fatigue life of the SMA 10 increased by an average 11% (for MR6) and 8% (for MR10), as shown in Figure 18. These improvements in average fatigue life increased to 52% and 46% for the DGA 20 mixture, for MR6 and MR10, respectively (Figure 19).

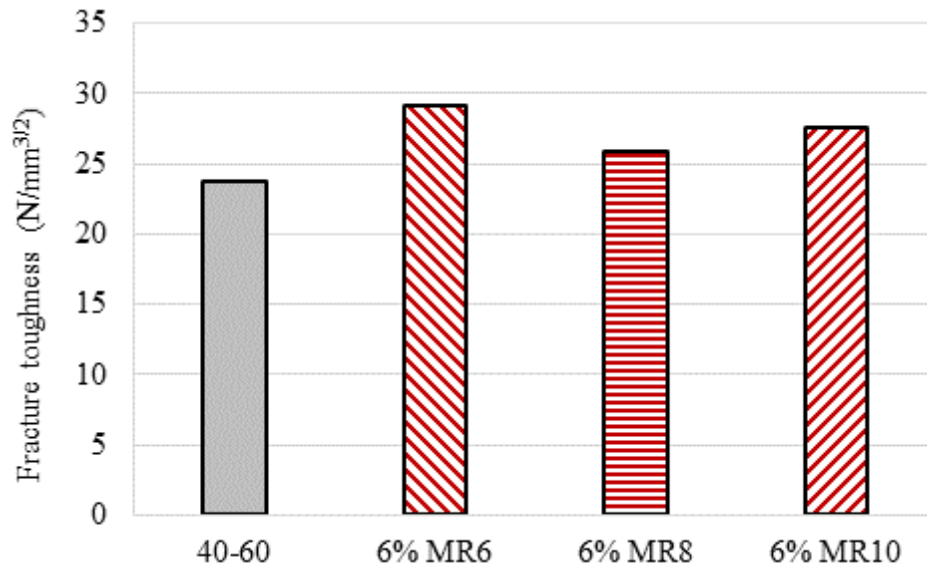


FIGURE 17 Effect of recycled plastic on SMA 10 fracture toughness (8).

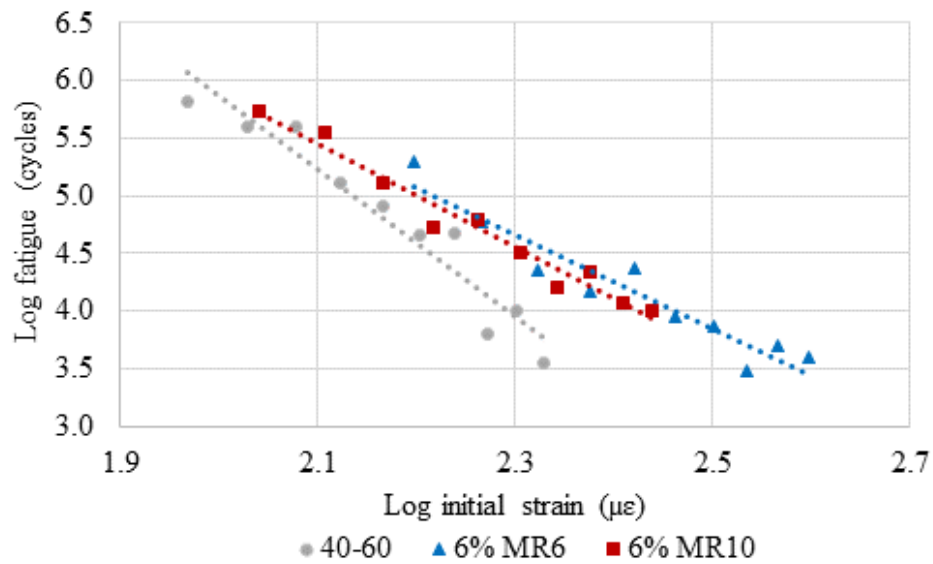


FIGURE 18 Effect of recycled plastic on SMA 10 fatigue life (9, 11).

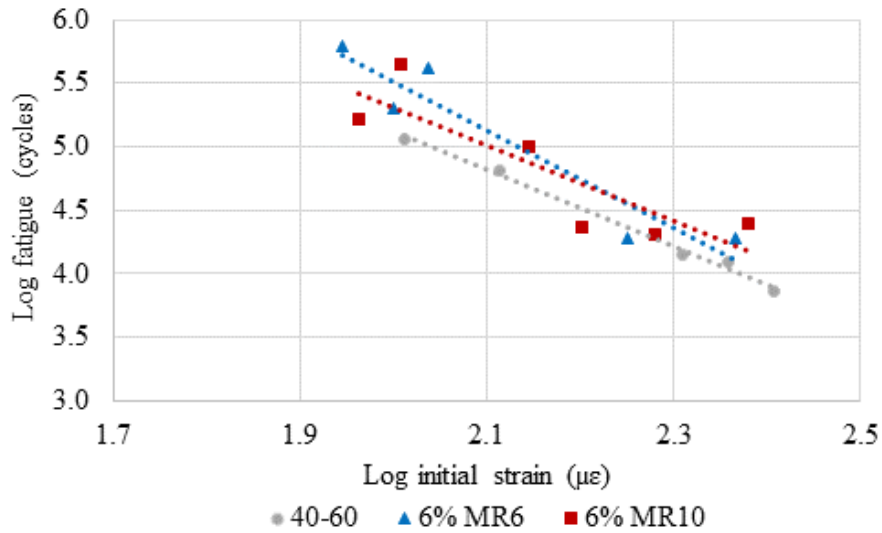


FIGURE 19 Effect of recycled plastic on DGA 20 fatigue life (9, 11).

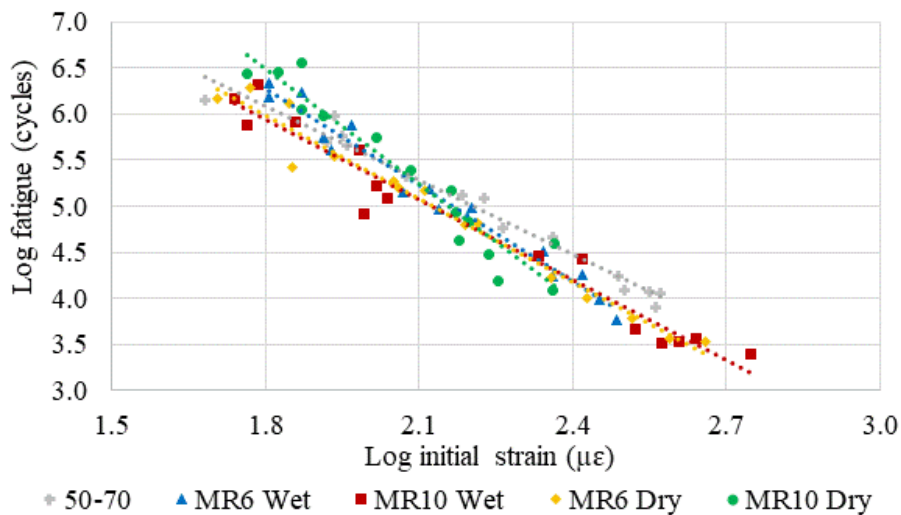


FIGURE 20 Effect of recycled plastic on UK DGA 10 fatigue life (14).

In similar work, the fatigue life of a typical UK DGA 10 was measured for otherwise nominally identical mixtures produced with unmodified 50–70 penetration asphalt, as well as with recycled plastic incorporated by dry-mixing and wet-mixing processes (14). The fatigue life relationships were generally similar (Figure 20) and the associated fatigue life models were not significantly different (p -values 0.33 to 0.74). Furthermore, the production method (wet-mixing versus dry-mixing) had no significant effect on the fatigue lives measured (p -value 0.49). The same research also measured Marshall Flow and the results indicated only minor differences in the results associated with the unmodified and RPM asphalt binders (Figure 21).

In Australia, the fatigue life of otherwise nominally identical DGA 10 was measured (in quadruplicate) for asphalt concrete mixtures with and without RPM asphalt binder (12). Although the mixtures with recycled plastic had a lower average fatigue life

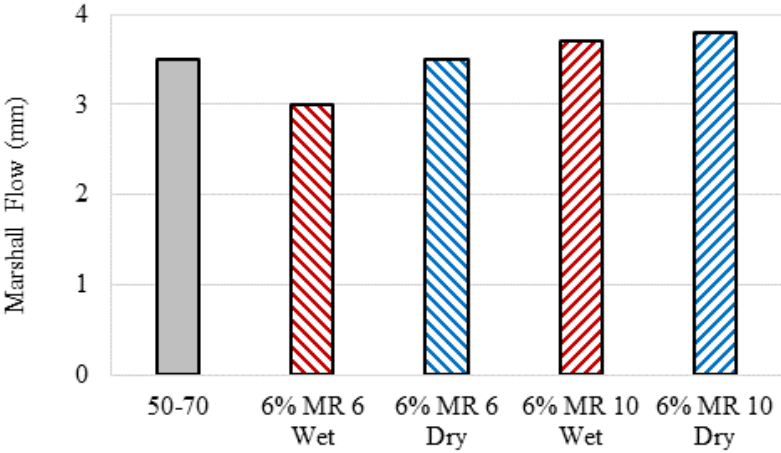


FIGURE 21 Effect of recycled plastic on UK DGA 10 Marshall Flow (14).

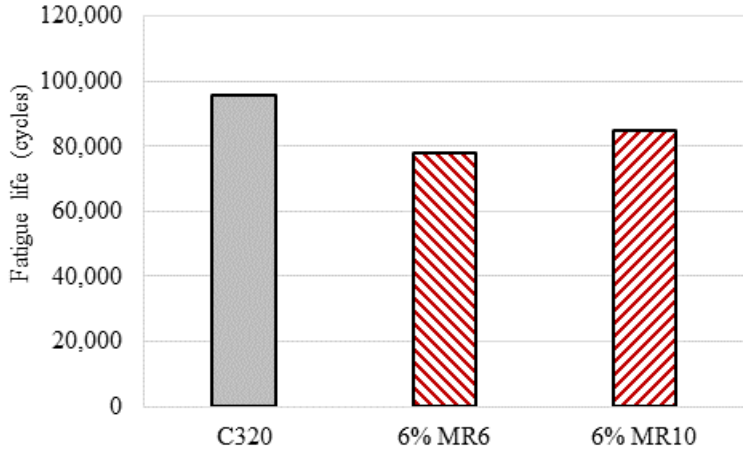


FIGURE 22 Effect of recycled plastic on average Australian DGA 10 fatigue life (12).

(Figure 22) the results were not statistically significant, with p-values of 0.32 (for MR6) and 0.67 (for MR10). That is, RPM asphalt binder did not significantly change the fatigue life of the asphalt concrete mixtures. The same research also found no significant difference in the Marshall Flow values for the unmodified and modified mixtures (Figure 23), with p-values of 0.61 (for MR6) and 0.39 (for MR10).

Based on the results of various asphalt concrete types commonly used in Australia and the UK, the additional of MR6 and MR10 were either associated with a moderate increase in crack resistance, or no significant change in crack resistance, when compared to otherwise identical unmodified mixtures. This is comparable to the effect of modification with conventional plastomeric polymers, such as EVA. In contrast, conventional elastomeric polymers, such as SBS, are generally associated with significantly greater improvement in cracking resistance of asphalt concrete mixtures.

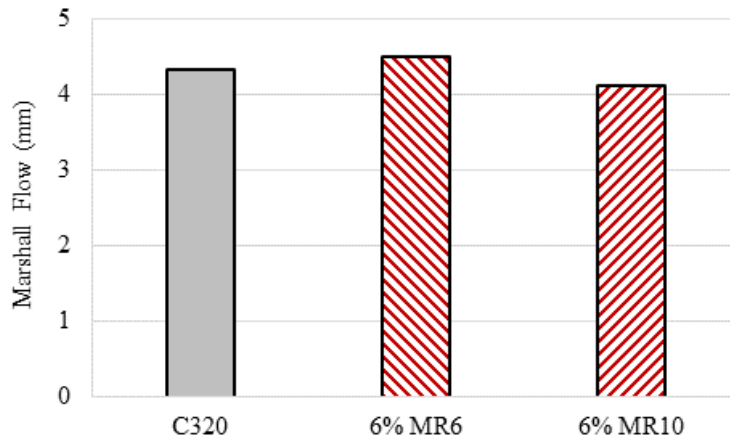


FIGURE 23 Effect of recycled plastic on average Australian DGA 10 Marshall Flow (12).

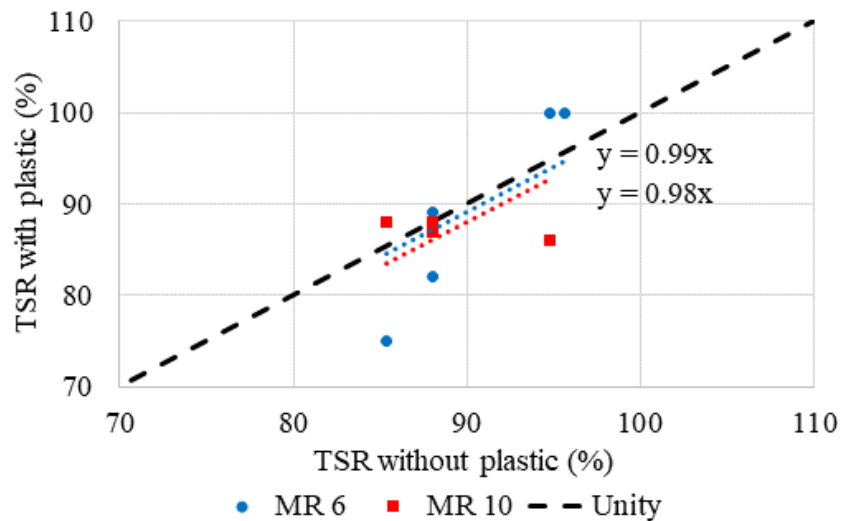


FIGURE 24 Effect of recycled plastic on mixture tensile strength ratio (TSR) value (8, 12, 14).

Moisture Damage Resistance

Moisture damage resistance is commonly expressed as the tensile strength ratio (TSR) which is the ratio of the indirect tensile strength for conditioned and unconditioned samples, which is also known as the Lottman, or modified Lottman (depending on the conditioning protocol) test. The TSR was calculated from tensile strength measurements for UK SMA 10 and DGA 20 (8), for UK DGA 10, by dry-mixing and wet-mixing (14), and for Australian DGA 10 (12). In some cases, the TSR was lower for the RPM mixtures, whereas in other cases, the TSR was higher for the RPM mixtures (Figure 24). Overall, the effect of recycled plastic on TSR was not significant, with p-values of 0.72 and 0.52, for MR6 and MR10, respectively. On average, the TSR for asphalt concrete mixtures modified with recycled plastic binder was 99% of the value associated with unmodified mixtures. That is, the additional of recycled plastic did not change the moisture damage resistance of the various asphalt concrete mixtures.

SUMMARY OF EFFECTS

The commercially available recycled plastic products described in this section for asphalt binder and asphalt concrete mixture modification have been added to various unmodified asphalts and to various mixture types, and the effects measured using a range of tests commonly specified in Australia and the UK, as well as for PG rating system commonly used in the USA. The results are below (Table 6). Recycled plastic products increased the resistance to asphalt binder flow and asphalt concrete deformation resistance. Significant ductility and elasticity were introduced to the asphalt binders, but the effect on asphalt concrete cracking resistance was either moderate or not significant. There was no significant difference in the asphalt concrete mixture moisture damage resistance, but the mixture stiffness increased two- to three-fold. The effects of MR6 and MR10 were generally similar to the effects associated with conventional polymer modification of asphalt binders and asphalt concrete mixtures, particularly those effects associated with the elastomeric polymer EVA.

TABLE 6 Summary of Effects of Recycled Plastic on Binder and Mixtures

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

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