DEPARTMENT OF TRANSPORTATION

Use of Plastics in Road Materials (Paving)

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16. Abstract (Limit: 250 words)

Limited local availability often constrains the growing demand for high-quality aggregate materials in road construction. To address this challenge, recycled waste materials, including plastics, are being explored as sustainable alternatives. This study investigates the feasibility of incorporating recycled plastics into asphalt and concrete pavements to enhance sustainability and reduce landfill waste. Comprehensive laboratory testing was conducted to evaluate the performance of plastic-modified asphalt and concrete. Asphalt mixtures were produced using the wet process method and assessed for binder performance, cracking resistance, and moisture susceptibility. Concrete mixtures incorporating recycled plastics as aggregate replacements were analyzed for workability, mechanical strength, and durability. The test results on plastic-modified asphalt indicated a reduced cracking resistance of the mixture when Post-Consumer Recycled (PCR) plastic was added to the binder using a wet process as compared to the same mixture with the same binder without plastic. In concrete mixtures, incorporating plastic materials either maintained statistically similar mechanical and durability properties (when used as plastic sand) or enhanced them (when used as plastic fiber). Integrating recycled plastics into road construction offers a sustainable solution for reducing landfill waste, lowering carbon emissions and promoting a circular economy.

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Use of Plastics in Road Materials (Paving)

Final Report

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Nomenclature

Symbol	Meaning
MRF	Materials Recovery Facility
RPS	Recycled plastic supplier
PMB	Polymer Modified Bitumen
PCR	Post-consumer recycles content
RAP	Reclaimed Asphalt Pavement
RPMA	Recycled polymer modified asphalt
RET	Reactive Terpolymer
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
HMW	High Molecular Weight Polyethylene
PP	Polypropylene
V or PVC	Polyvinyl Chloride
PET	polyethylene terephthalate
ABS	Acrylonitrile butadiene styrene
HIPS	High Impact Polystyrene
GPPS	General Purpose Polystyrene
TPE	Thermoplastic elastomer
TPO	Thermoplastic Polyolefins
LCA	Life-cycle assessment
RPM	recycled plastic-modified
PG	Performance Grade
PIR	post-industrial recycled
HMA	hot mix asphalt
WMA	Warm mix asphalt
AG	Additive Group
LCCA	Life-cycle cost analysis
PFAS	per- and polyfluoroalkyl substances
ITZ	Interfacial Transition Zone
PIR	post-industrial recycled
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
Delta (δ)	Phase Angle
DSR	Dynamic Shear Rheometer
G*	Complex Shear Modulus
RAP	Reclaimed Asphalt Pavement
IDEAL-CT	Indirect Tension Asphalt Cracking Test
LLD	Load-Line Displacement
MSCR	Multiple Stress Creep Recovery
NMAS	Nominal Maximum Aggregate Size
PCR	Post-Consumer Recycled
SGC	Superpave Gyratory Compactor

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Executive Summary

The increasing demand for sustainable infrastructure solutions has increased interest in using recycled plastics in road construction. This study explores the feasibility of incorporating plastics into asphalt and concrete paving materials. The research aims to provide an environmentally friendly alternative to conventional road materials while addressing the growing issue of plastic waste accumulation.

A comprehensive literature review was conducted to assess global and national practices in using recycled plastics for road applications. The study identified different plastic types, material properties, and processing methods used in asphalt and concrete mixtures. Key considerations included the influence of plastics on mechanical performance, durability, and environmental impacts. Additionally, surveys and interviews were carried out to gather insights from plastic suppliers and producers regarding the new products made from recycled plastic and the opportunities and practical challenges of plastic-modified pavements.

Extensive laboratory testing was performed to evaluate the effects of incorporating plastic waste in asphalt and concrete mixtures. Asphalt mix designs were developed using the process method, with various plastic concentrations tested for their impact on binder performance, cracking resistance, and moisture susceptibility. Similarly, concrete mixtures incorporating recycled plastics as aggregate replacements and additives were analyzed for compressive strength, flexural properties, shrinkage, and workability. The test results on plastic-modified asphalt indicated a reduced cracking resistance of the mixture when Post-Consumer Recycled (PCR) plastic is added to the binder using a wet process as compared to the same mixture with the same binder without plastic. Incorporating plastic materials reduced concrete's workability and air content, with plastic fibers further improving tensile, flexural, and durability properties. While plastic fibers increased compressive strength, recycled plastic sand lowered it due to weaker bonding with cement paste.

Despite these advantages, challenges such as phase separation in asphalt, variability in plastic quality, and potential long-term durability concerns were identified. Addressing these challenges requires further research, including large-scale field trials and long-term performance monitoring.

The results of this research provide MnDOT and local road agencies with valuable data to support the integration of recycled plastics into transportation infrastructures. By adopting recycled plastics in road construction, transportation agencies can reduce landfill waste, lower carbon footprints, and promote a circular economy in sustainable infrastructure development.

The continued advancement of material processing technologies, performance monitoring, and collaborative efforts between research institutions and industry stakeholders will be crucial in realizing the full benefits of plastic-infused road materials.

Chapter 1: Introduction

1.1 Background

While the demand for high-quality aggregate materials for constructing highway and local road systems has increased, there is often local insufficiency of such materials, leading to the need for alternative solutions. Recycled waste materials have been used in road construction to the maximum possible economic extent, achieving equal or improved performance compared to traditional materials. Among these waste materials, plastic is a significant contributor to environmental pollution, with millions of tons generated annually across the United States. Recent bans on importing plastic waste by developing countries have further intensified the urgency to address plastic waste issues. This shift has spurred U.S. cities and states to focus more seriously on transforming plastic waste into valuable materials rather than allowing it to accumulate in landfills.

There has been a growing interest in incorporating recycled plastics into road materials, aiming to enhance the performance of pavements while reducing environmental impact. Research initiatives are exploring various methods of integrating recycled plastics into asphalt and concrete, with promising results that demonstrate enhanced durability, strength, and longevity.

The integration of recycled materials into construction not only addresses material shortages but also aligns with broader sustainability goals. By diverting waste from landfills and reducing reliance on virgin materials, these practices contribute to a circular economy where materials are continuously reused and recycled. Moreover, the environmental benefits extend beyond waste reduction. Using recycled plastic can lower the carbon footprint associated with material production, as it reduces the need for energy-intensive extraction and processing of natural resources. Furthermore, incorporating recycled materials can reduce the transportation-related environmental impact by sourcing locally available materials.

As research and technology in this field continue to advance, the construction industry is increasingly adopting innovative solutions that incorporate recycled materials. This trend promotes environmental stewardship and resource efficiency and offers a sustainable pathway for the future of infrastructure development. The widespread implementation of these materials will play a crucial role in reducing the environmental footprint of construction projects while also delivering cost-effective, durable solutions for road maintenance and development.

1.2 Research Objectives

This research study focused on the following key factors:

- Survey the use of recycled plastics for roads in coordination with literature review results
- Evaluate the feasibility of using plastic waste in paving mixtures (asphalt and concrete)
- Recommend applications that would be most beneficial and practical
- Work in partnership with the Minnesota Department of Transportation (MnDOT) to provide a summary of the work being done both locally and within the pooled-funded studies

- Work with MnDOT/MnROAD to demonstrate proof-of-concept for the beneficial applications of the recycled plastic and identify practical challenges associated with its full implementation in Minnesota’s transportation infrastructure system.

The outcomes of this project will benefit MnDOT and Minnesota local road agencies by addressing their need to incorporate sustainability principles and practices into highway and local road projects. This project helps reduce landfill waste and provides a recycled paving material that offers equal or improved performance, maximizing economic and practical potential. This work also provides sustainable alternative solutions for plastic waste materials, a growing issue in Minnesota and other states. These innovative solutions and technologies are being implemented in the Minnesota transportation infrastructure system to ensure environmental quality, public health, safety, and substantial economic savings for Minnesota.

1.3 Organization of the Report

This report includes seven chapters. Chapter 1 describes the background and objectives of the study. Chapter 2 provides a comprehensive literature review of current practices for using plastic materials in asphalt and concrete pavements. Chapter 3 summarizes the identification and procurement of promising recycled plastic materials through surveys and interviews. Chapter 4 discusses the comprehensive laboratory investigation into the feasibility of using plastic waste in asphalt paving mixtures. Chapter 5 examines the feasibility of using plastic waste in concrete paving mixtures. Chapter 6 outlines the research benefits and implementation steps, highlighting the study's outcomes and how MnDOT and local transportation agencies could implement the findings. Chapter 7 presents the conclusions, challenges, and recommendations for future studies. The developed surveys are included in Appendix A, and the chemical composition of the cementitious materials collected from the companies, as well as the gradation and physical properties of the aggregates used in concrete, are listed in Appendix B.

Chapter 2: Literature Review

This chapter explores international, national, and state-level studies on using recycled plastic materials in roadway applications, including asphalt concrete (AC) and Portland cement concrete (PCC). It will critically analyze reports and recent road trials from the U.S. and other countries, focusing on recyclable plastic waste materials, plastic recycling processes, and methods for incorporating recycled plastics into road construction materials. Additionally, this chapter assesses proprietary and non-proprietary products used in global road trials, evaluating their performance and cost-effectiveness while addressing environmental and occupational health impacts, such as concerns about microplastics and Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) substances.

The main content of this chapter has been adapted from a review paper published by (Hasheminezhad et al., 2024) in the Construction and Building Materials journal, with permission from Elsevier as the publisher.

2.1 Background

Plastic is a common term used to describe various types of synthetic or semi-synthetic organic amorphous solid materials used in the production of industrial items (Belmokaddem et al., 2020; Lopes et al., 2015). Coal, crude oil, and cellulose from plants and trees are examples of organic compounds from which plastic can be manufactured (Canopoli et al., 2020). Polymers of high molecular weight make up the majority of plastics, although they may also include additional ingredients to boost functionality and reduce costs. Various synthetic and semi-synthetic applications utilize plastic (Abukhettala and Fall, 2021), with the most common uses including plastic utensils, plastic wraps, and soft drink bottles. While plastics are used because they are simple to manufacture, inexpensive, and durable, these useful qualities may, unfortunately, result in plastic becoming a huge pollution problem. Its persistence in the environment can do great harm, and the continued generation of plastic waste is now causing massive trash dumps. Waste disposed in streams, roads, and open land regions endangers human health and the environment (Rai et al., 2020). The Organization for Economic Co-operation and Development (OECD) indicated in a new report that the world is generating twice as much plastic waste as it did 20 years ago, most of it going into landfills, being burned, or leaking into the environment, with only 9% being effectively recycled (Biber et al., 2019; Pan et al., 2020). A large amount of plastic generated yearly is dumped into the ocean, resulting in more pollution and harm than people could have imagined. Without adequate waste management, the reported rate of ocean and sea pollution will likely reach catastrophic levels by 2025, which is predicted to increase by 10 times its current level. Macro-plastics and micro-plastics are two categories of plastic pollution. Macro-plastics are large, easily observable plastics larger than 5-millimeter length, while micro-plastics are often products that have undergone processes to break them down into tiny particles less than five millimeters in length, about the size of a sesame seed (Iravanian and Ahmed, 2021). Research indicates that land is subjected to significantly greater levels of micro-plastic pollution than either freshwater environments or the ocean (Iravanian and Ahmed, 2021). The main issues associated with plastics are that they cannot be safely burned because they endanger living beings by releasing hazardous fumes (solid particles generated by condensation from the gaseous state, generally after volatilization from a melted substance) and gases when burned (Iravanian and Haider, 2020). New and more advanced techniques are being developed daily to solve this issue. Because plastic waste can block drain pipes and damage marine and aquatic life, it should not be deposited into bodies of water. Although available land is scarce, if plastic wastes could be immediately recycled, their disposal could become relatively easy (Rai et al., 2020). To safeguard our planet and the future of the next generation, a safe and efficient means for disposing of plastic trash is critically needed.

Although many biodegradable plastics are being developed to compensate for plastic's negative effects, this is not a sufficient solution. One of the simple ways to solve the plastic pollution problem is through recycling and reusing (Irwan et al., 2016; Lu et al., 2019). Governments encourage the reuse or recycling of plastic so that low-cost plastic widely used by urban residents can be reused, reducing the adverse effects of plastic. Unfortunately, recycling plastic has proven difficult; the most significant issue is its labor-intensitivity and challenges in sorting plastic waste objects (Eltayeb and Attom, 2021; Irwan et al., 2016). Moreover, plastic wastes are mainly composed of multiple types of polymers, sometimes affixed with fibers for increased strength. This makes recycling challenging, especially when uniform quality byproducts are the aim. To find effective ways to reuse these materials in civil engineering applications while minimizing pollution, several studies have been performed on applications that include use as a bitumen modifier, a binder modifier, an aggregate extender in asphalt pavements, and an additive in concrete pavements. This chapter thoroughly examines the incorporation of recycled plastics in asphalt and concrete infrastructure systems, encompassing their effects on content, size, and shape, as well as considering the environmental implications of integrating these discarded materials into civil engineering applications. An overview of proprietary and non-proprietary products employed in pavement construction trials is also provided. This chapter also addresses the potential environmental, occupational health, and safety implications of plastic use in such contexts. For this purpose, a thorough investigation of technical literature, particularly on recent literature pertinent to the most recent advances in the field, was conducted.

2.2 Summary of Use of Recycled Plastics

2.2.1 Types of Plastics

Plastics (polymers) are classified into two types based on their thermal behavior: thermosetting and thermoplastic. A thermosetting plastic cannot be softened or remolded by heat; in other words, it cannot endure heat. On the other hand, thermoplastics are heated up and molded to create new forms (Sulyman et al., 2014). Examples of materials that comprise either of these types are shown in Table 2.1, and a summary of recycled plastic descriptions and sources used as thermoplastics is presented in Table 2.2.

Table 2.1 Thermosetting and Thermoplastics examples (Anum and Job, 2021; Barbaroux et al., 2021; Sulyman et al., 2014)

Thermoplastics	Thermosetting
Polyethylene Terephthalate (PET or PETE)	Bakelite
Polypropylene (PP)	Epoxy
Polyvinyl Acetate (PVA)	Melamine
Polyvinyl chloride (V)	Polyester

Thermoplastics	Thermosetting
Polystyrene (PS)	Polyurethane
Low-density polyethylene (LDPE)	Urea – Formaldehyde
High-density polyethylene (HDPE)	Alkyd
Other include materials made with more than one plastic type from other categories	

2.2.2 Current Scenario of Plastic-Waste Recycling

As mentioned earlier, plastic waste can contain both organic (food remains) and inorganic elements, making recycling difficult. The practice of reclaiming waste or scrap plastic and turning the materials into useable products is known as plastic recycling (Kamaruddin et al., 2017), described as follows (Chin et al., 2020):

- **Step 1. Collecting:** the waste materials, including plastic, are collected from local curbsides, then delivered and co-mingled into a local materials recovery facility (MRF).
- **Step 2. Sorting:** The waste materials in the local MRF are automatically or manually sorted to ensure that all contaminants are removed from the plastic waste stream.
- **Step 3. Reprocessing:** The reprocessing step involves shredding, washing, melting, and pelletizing to produce a pure stream of a single recycled plastic type.
- **Step 4. Recycled-plastic production:** uniform-sized pellets of recycled plastic are produced that can then be used as raw material to be molded into functional and valuable plastic goods.

High-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), and polypropylene (PP) are the most frequently recycled plastic types (Wu and Montalvo, 2021). Recycling centers are central locations where sorting waste plastic is performed (Kamaruddin et al., 2017). Other plastic material types are rarely recycled due to their risk of becoming stuck in the recycling facility's sorting equipment and causing breakage or stoppage (e.g., PS), as well as the fact that their recycling is not economically feasible. An overview of a typical plastic recycling chain is shown in Figure 2.1. Table 2.3 summarizes the available plastics, their recycling potential, and the risks associated with incineration. The end-of-life (EOL) treatment method for these commercially available plastics reflects the fate of the incorporated additives. Table 2.4, in turn, summarizes the fate of additives of interest in plastics.

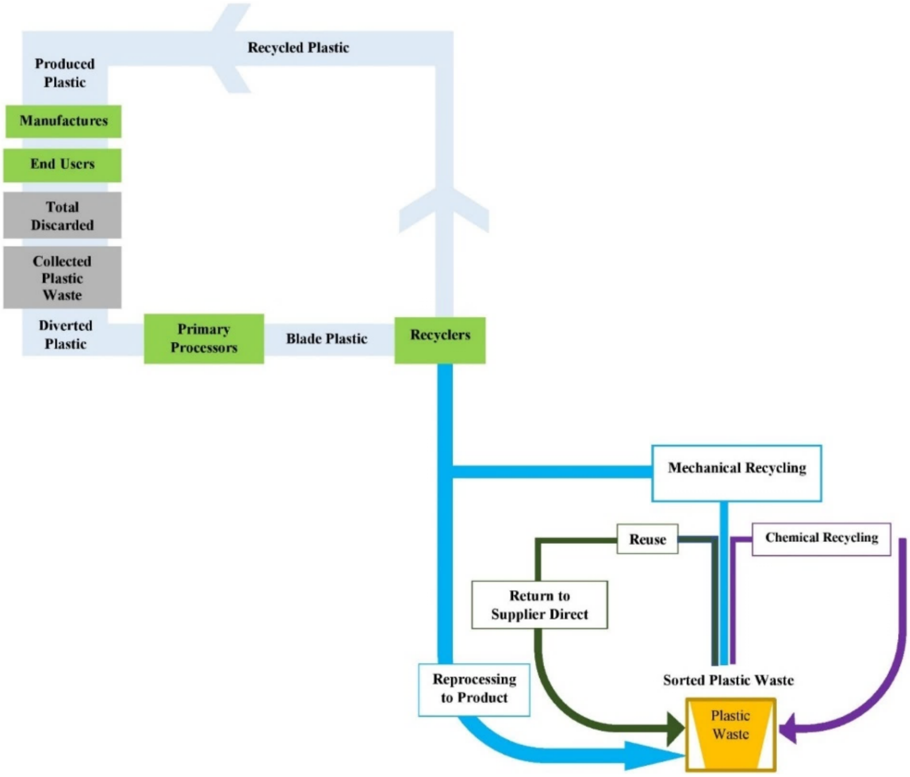

Figure 2.1 Overview of Plastics Recycling Chain Modified from (Hopewell et al., 2009; Milios et al., 2018)

Table 2.2 A Summary of Recycled Plastic Description and Sources. Sources of data: (Faraj et al., 2020) (Basha and Babay, 2015; Jayalath et al., 2021; Jmal et al., 2018; Kamaruddin et al., 2017; Siddique et al., 2008; Wu and Montalvo, 2021)

Recycling Symbol	Common Characteristic	Major Physical and Chemical Properties	Some Products and Sources	Some Common Use for Recycled Plastic
1 PET Polyethylene Terephthalate (PET or PETE)	Clear hard plastic, suitable for fiber	• Highly flexible, colorless and semi-crystalline resin in its natural state. • Good dimensional stability, resistance to impact, and moisture. • Thermoplastic polymer • Density 1.15±0.03 g/cm3, tensile strength 0.8±0.14 N/mm2. • Biodegradable.	Single-use drink bottles and vegetable oil containers.	Packaging and wrapping
2 HDPE High-density polyethylene (HDPE)	Commonly used plastic, white or colored	• Melting point: 120-140°C. • Density: 0.93 to 0.97 g/cm3. • Continuous temperature: -50°C to +60°C, relatively stiff material with useful temperature capabilities. • Higher tensile strength compared to other forms of polyethylene. • Having good chemical resistance and non-toxic. • Stronger, denser, and more rigid than LDPE. • Non-biodegradable.	Milk jugs, bottle caps, detergent and cleaner bottles, and shampoo bottles.	Mobile rubbish bins and detergent bottles
3 PVC Polyvinyl Chloride (V or PVC)	Hard rigid plastic	• Strong, lightweight, and durable. • High chemical stability and bio-compatibility, chemical resistance, and low cost. • Density: 0.77 to 0.88 g/cm3. • Relatively impervious to sunlight and weather. • Never Biodegradable.	Mineral water bottles, plumbing pipes & gutters; medical disposables, wire jacketing, cooking oil bottles, teething rings.	Industrial flooring and dishwasher bottles

Recycling Symbol	Common Characteristic	Major Physical and Chemical Properties	Some Products and Sources	Some Common Use for Recycled Plastic
LDPE Low-density polyethylene (LDPE)	Soft and flexible plastic	• Melting point: 105 to 115°C. • Density: 0.910–0.940 g/cm^3 • Temperature resistance up to 80°C continuously and 95°C for shorter times. • Low-cost polymer with good processability. • High impact strength at low temperatures, good weather ability. • Tensile strength 0.20-0.4 N/mm^2.	Cosmetic and detergent bottles, sheeting, squeezable bottles, general packaging, carry bags, and sacks.	Plant, packaging, and nurseries bags
PP Polypropylene (PP)	Hard but flexible plastic	• Good chemical resistance and good fatigue resistance. • Good heat resistance and flexibility at low temperatures. • Excellent resistance to most solvents. • Specific heat capacity: 1520 J/(kg.K) at 20°C. • Melting point: 160 – 168°C. • Density: 0.9 g/cm^3. • Biodegradable.	Straws, wrappings, wrappers of detergent, biscuit, vapors packets, caps, syrup and medicine bottles.	Compost bins and worm factories
PS Polystyrene (PS)	Stiff but brittle plastic, clear and glossy	• Density 1.1±0.19 g/cm^3. • Tensile strength 3±1.13 N/mm^2. • Melting point: 210-249°C. • Non-biodegradable.	Disposable plates, cups, egg cartons, compact disc cases, yogurt pots, and protective packaging.	Video/CD boxes
O All other Plastics	Foamed, lightweight, energy absorbing, and thermal insulation	• Thermoplastic polymer. • Very durable, stiff, and strong. • Inability to withstand ultraviolet radiation from the sun. • Glass transition temperature 105°C; no true melting point due to amorphous. • Non-Biodegradable.	Acrylonitrile butadiene styrene (ABS): Most general e-plastics used for electronic devices.	Video/CD boxes

Recycling Symbol	Common Characteristic	Major Physical and Chemical Properties	Some Products and Sources	Some Common Use for Recycled Plastic
		• Specific gravity: 0.92. • Processing temperature: 65-80°C. • Melting flow index: 2.5 g/10min. • Non-biodegradable.	Ethylene-vinyl acetate (EVA)	
		• Good dimensional stability and good flame resistance. • High stability to different environmental conditions. • Specific gravity 1.2. • Compressive strength 86.1 MPa, and Tensile modulus 2.37 MPa. • Melt flow index: 2.6 g/10 min. • Biodegradable.	Polycarbonate (PC): CDs and DVDs.	
		• Density 1.12 g/cm3. • Tensile strength 45 N/mm2. • A thermostable polymer. • Not hazardous waste.	Polyurethane (PU): Most commonly used in thermal insulation of buildings, technical equipment, and medical devices.	
			Some sports drink bottles, sunglasses, and large water cooler bottles are available.	

Table 2.3 A summary of available treatment potentials for plastics. Source of data and information: (Alassali et al., 2021)

NO.	Plastic type	Critical Ingredients	Recycling Potential	CO_2 Saving through Recycling	What Happens by Incineration?	Most Probable Fate of Additives
1	Polyethylene terephthalate (PET)	None; PET does not contain plasticizers. Terephthalate compounds in PET are not volatile. Antimony is present in negligible concentrations.	Can endure up to 8 recycling cycles. PET is turned into fibers, films, bottles, etc.	Recycling produces 82% less CO_2 than the production of new PET (transportation is considered).	Residue-free combustion. If FRs-free, only CO_2 and H_2O are produced.	Transmitted to new products when recycled unless it has volatile or reactive properties.
2	Polyethylene (PE)	Plasticizers are not required.	4 to 5 times; the decrease in polymeric chains' length will prevent further recycling.	Recycling produces 20–70% less CO_2 than manufacturing new PE.	Residue-free combustion. If FRs-free, only CO_2 and H_2O are produced. Hydrated aluminum oxides are the most used Flame retardants; quantitatively, they are ecologically safe.	Transmitted to new products when recycled unless it has volatile or reactive properties.

NO.	Plastic type	Critical Ingredients	Recycling Potential	CO_2 Saving through Recycling	What Happens by Incineration?	Most Probable Fate of Additives
3	Polypropylene (PP)	The use of plasticizers is uncommon.	PP can be recycled, but it is not extensively applied. When PP is melted down, various PP types are delivering low-quality recycled mat	Recycling produces 20–70% less CO_2 than manufacturing new PP.	Residue-free combustion. If FRs-free, only CO_2 and H_2O are produced. Hydrated aluminum oxides are the most used Flame retardants; quantitatively, they are ecologically safe.	Mostly liberated to the environment (for the incinerated fraction). When mechanically recycled, the additives are transmitted to new products.
4	Polystyrene (PS)	P-nonylphenol is partly used as a stabilizer for PS, a substance with estrogen-like activity.	Poor recyclability. PS can be converted into the starting material styrene by heating.	No available information.	PS usually contains additives (e.g., Flame retardants). Hence, pungent and harmful odors are foreseen.	Additives are liberated to the environment.

NO.	Plastic type	Critical Ingredients	Recycling Potential	CO_2 Saving through Recycling	What Happens by Incineration?	Most Probable Fate of Additives
5	Polyvinyl chloride (PVC)	Usually phthalates. Sometimes, p-nonylphenol and BPA are other so-called endocrine disrupters (hormone-like substances).	Germany has widespread take-back systems of the PVC processing industry for rigid PVC construction material.	No available information.	Forms corrosive hydrogen chloride gas and becomes hydrochloric acid with water. This is neutralized with lime. Toxic dioxins may be formed. If incineration is incomplete, smoke and soot may contain toxic poly-condensed aromatics.	Mostly liberated to the environment.

Table 2.4 A summary of the fate of additives of interest in plastics. Source of data and information (Alassali et al., 2021)

NO.	Substance	Function	Relevant Types of Plastics	Potential Release from Plastics	Fate of the Ingredient by Recycling
1	Cadmium (Cd) and cadmium compounds	Pigments: colors include yellow, orange, red, and all other derived colors; heat and UV stabilizer in PVC.	Cadmium pigments may be found in all types of resins. Cadmium stabilizers are mainly used in PVC.	This element and its compounds are solid-bound in plastics. Release only by wear and tear of products (insignificant quantity may be released).	Cd pigments and stabilizers are solidly bound; they will continue to exist in the plastics cycle when mechanically recycled.
2	Chromium (Cr) and chromium compounds	Catalyst for the production of plastics (chromium trioxide); in pigments (yellow, red, and green).	PVC, PE, PP, and other non-specified plastics.	This element and its compounds are solid-bound in plastics. Release only by wear and tear of products (insignificant quantity may be released).	Cr pigments will remain in the plastics' cycle by mechanical recycling.
3	Chromium trioxide	Catalyst for production of plastics; intermediate for manufacturing of pigments.	PE and other plastics.	Mostly solid bound; insignificant fractions may be lost only by wear and tear.	Cr compounds will stay in the plastics' cycle by mechanical recycling.
4	Cobalt (II) diacetate	Pigment for tinting PET a bluish color (phased-out); catalyst, e.g., in producing Purified Terephthalate Acid, an intermediate for polyester fiber).	Polyester (PET).	It is not expected to migrate (it is solid bound). Release only by wear and tear of plastics. The potential for release from plastics is trivial.	When mechanically recycled, it will be sustained in the plastics' cycle, but a minor amount may be washed out due to the high water solubility.

NO.	Substance	Function	Relevant Types of Plastics	Potential Release from Plastics	Fate of the Ingredient by Recycling
5	Mercury (Hg) and mercury compounds	Used as a catalyst.	Polyurethane (PUR).	Mercury compounds are not chemically bound and will migrate. Elemental mercury will vaporize from the plastic material.	PUR can only be recycled by energy recovery or feed-stock recycling. Most mercury will probably evaporate. Unknown fates of Hg by chemical recycling.
6	Brominated flame retardants (BFRs)	Flame retardants.	ABS, EPS, HIPS, PA, PBT, PE, PP, epoxy, unsaturated polyesters, and PU.	Flame retardants can be either reactive or additive. Only additive flame retardants will migrate.	BFRs will probably remain in mechanically recycled plastics and decompose by incineration.
7	Hexabromocyclododecane (HBCDD) and all major diastereoisomers	Flame retardant.	Expandable and extruded polystyrene (EPS and XPS), HIPS, synthetic blends.	HBCDD is not chemically bound and will migrate.	There is a chance of partial evaporation by recycling, but mainly it will remain. It will decay by incineration.
8	Ethylene (bistetrabromophthalimide) (EBTEBPI)	Flame retardant.	HIPS, PE, PP, PBT, OPET, PC, and engineering thermoplastics in general	High molecular weight (951.5 g mol−1), high melting point (446°C) and low vapor pressure. Hence, migration is unlikely.	It will mostly remain in the recycled materials by mechanical recycling.

NO.	Substance	Function	Relevant Types of Plastics	Potential Release from Plastics	Fate of the Ingredient by Recycling
9	Decabromodiphenyl ethane (DBDPE)	Flame retardant.	CPE, engineering thermoplastic, HIPS, PE, PP, thermosets.	Due to the high molecular weight (971 g mol−1) and boiling point (676°C), migration is unpredicted.	It will mostly remain in the recycled materials by mechanical recycling.
10	Tetrabromobisphenol A bis-(2,3- dibromo propyl) ether (TBBPA-BDBPE)	Flame retardant.	ABS, HIPS, Phenolic resins, epoxy-laminates.	It is chemically bound (reactive FR); release is limited.	These substances will predominantly be sustained in the plastics cycle by mechanical recycling, yet they will decompose by incineration.
11	Antimony trioxide (Sb_2O_3)	Synergic flame retardant, stabilizer.	Various plastics.	It is solid-bound (inorganic) and possibly will not migrate. Estimated to be only liberated by tear and wear.	Sb_2O_3 will be preserved in plastics by mechanical recycling and decompose by incineration.
12	Polycyclic aromatic Hydrocarbons (PAHs)	They are impurities found in plasticizers (e.g., mineral oil and coal-based extender oils) and carbon black.	All black plastics. Soft plasticized plastics and other plastic types such as ABS and PP.	Some products have substantial discharge, and thereby, dermal exposure can be predicted.	It will remain in the cycle by mechanical recycling due to the low mobility and the high affinity to the plastic matrix.

2.3 Review of Recycled Plastic Utilization in Asphalt-Based Infrastructure Applications

Asphalt, the most common road paving material, is prone to several distresses, potentially resulting in a decrease in the quality and performance of road pavement (Aburawi, 2018). Any improvement in the service life of road pavements will undoubtedly have significant economic benefits, and improvements to asphalt are all directed toward increasing their useful life and performance (Heydari et al., 2021; Sulyman et al., 2014). The application of recycled plastics as reliable modifiers for asphalt pavement development can also address the global issue of disposing of plastics in landfills (Ahmadinia et al., 2011; Ahmad, 2014; Ajam, 2013; Mohamady Abd-Allah et al., 2014). The use of recycled plastic in asphalt production, either as an aggregate extender (as shown in Table 2.5), a binder modifier (as shown in Table 2.6), or a bitumen extender (as shown in Table 2.7) will be discussed here.

According to the literature, recycled PET, in particular, is ideal for use in asphalt mixtures in road building. As an illustration, using PET would enhance flexible pavement's qualities by enhancing stability, stiffness, and viscosity, all of which would enhance resistance to rutting, thermal cracking, stripping, and fatigue damage (Al-Hadidy and Yi-qiu, 2009; Attaelmanan et al., 2011). Although there are many kinds of asphalt mixtures, since the use of recycled plastic is typically investigated for use in dense graded asphalt or asphalt concrete, it is strongly suggested that how recycled plastic works with various asphalt compositions like cold mix or stone matrix (mastic) asphalt be examined (Heydari et al., 2021; Sulyman et al., 2014). According to the literature, melted LDPE modifies the bitumen much more effectively than aggregate substitution; otherwise, specimens with a higher LDPE content would possess a higher binder content than the others. HDPE increases the stability value up to a certain inclusion content (Heydari et al., 2021; Sulyman et al., 2014). Because plastic inclusion percentages are higher, adverse effects can emerge. Due to plastic's ability to fill certain voids within the aggregate as it melts and covers the surface, the optimal binder content of the mixture might be diminished (Heydari et al., 2021). The total stiffness of the modified asphalt mixture is increased when recycled plastic with a low melting point is used (Heydari et al., 2021). There is a great need to clarify the impact of high rigidity on the fatigue behavior of a mixture.

Plastic waste can be integrated into asphalt mixes using either a dry or wet approach. In the dry method, plastic waste substitutes for a portion of the aggregate, while the wet method involves adding plastic waste to the asphalt binder to enhance its properties. Comparatively, the dry process has proven more economical than the wet process. The wet technique is particularly effective for plastics with lower melting points, enhancing the binder blends' resistance to rutting, moisture, and fatigue. However, plastics with higher melting points can elevate viscosity while diminishing the ductility of the binder blends.

Table 2.5 Recycled Plastic Utilization as an Aggregate Extender in Asphalt

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Asphalt Type	Influence on Asphalt Properties								Contents%	Proposed content (%)	Proposed size (mm)	References
			Length (mm)	Width (mm)	AR		Softening Point	Marshall Stiffness Modulus	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental-Friendly	Fatigue Resistance				
1	PET	Strip	5	5	-	Asphalt Concrete-Wearing Course (AC-WC)	-	↑	-		↑	-	-	-	1, 2, 3, 4, 5, 6, 7	-	-	(Machsus et al., 2021)
2	Mixed recycled plastic and three types of recycled glass, namely, bottle glass, LCD glass, and sheet glass	Powder	-	-	-	Hot Mixed Asphalt (HMA)	-	↑	-	-	↑	-	-	-	1-5 recycled plastic and 1-5 recycled glass	1% recycled plastic and 4% recycled glass	-	(Mustakiza Zakaria et al., 2018)
3	PET	Shred	-	-	-	Hot Mixed Asphalt (HMA)	-	↑	-	-	-	-	-	↑	15, 30, 50	-	-	(Azarhoosh et al., 2022, 2021)
4	LDPE	Strip	2	2	-	Hot Mixed Asphalt (HMA)	-	↑	-	-	-	-	-	-	0-5@2.5	2.5	-	(Lukjan et al., 2017)

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Asphalt Type	Influence on Asphalt Properties								Contents%	Proposed content (%)	Proposed size (mm)	References
			Length (mm)	Width (mm)	AR		Softening Point	Marshall Stiffness Modulus	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental-Friendly	Fatigue Resistance				
5	PET	Shred	-	-	-	High-viscosity-modified asphalt (HVMA)	-	-	-	-	-	-	-	↑	-	-	-	(Kamada and Yamada, 2002)
6	PET	Shred	-	-	-	Plastic Asphalt Mix	-	↑	-	-	↑	-	-	-	2-8@2	-	-	(Adou et al., 2018)
7	Plastic Wastes	Melted shredded	-	-	-	plastic-coated aggregate (PCA) asphalt	-	↑	-	-	-	-	-	-	-	-	-	(Asare et al., 2019)
8	PET and Polyethylene	Shred	-	-	-	Hot Mixed Asphalt (HMA)	-	↑	-	↑	-	-	-	↑	3-7@2	-	-	(Dhiman and Arora, 2021)
9	PP, LDPE and HDPE	Powder	-	-	-	Hot Mixed Asphalt (HMA)	-	↑	↑	-	↑	-	↑	-	2-8@2	8	-	(Sk and Prasad, 2012)
10	PET	Shred	2.36	-	-	Hot Mixed Asphalt (HMA)	-	↑	-	↑	-	-	↑	-	0.1-1.1@0.1	-	-	(A. M. Mosa et al., 2018)

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Asphalt Type	Influence on Asphalt Properties								Contents%	Proposed content (%)	Proposed size (mm)	References
			Length (mm)	Width (mm)	AR		Softening Point	Marshall Stiffness Modulus	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental-Friendly	Fatigue Resistance				
11	PP/PE	Shred	-	-	-	Asphalt Concrete	-	↑	-	-	-	-	-	↑	15,25	-	-	(Ballester-Ramos et al., 2023)
12	LDPE	pellet	-	-	-	Hot Mixed Asphalt (HMA)	-	-	-	↑	-	-	↑	↑	10	-	-	(Abdalfattah et al., 2022b)

Table 2.6 Recycled Plastic Utilization as a Binder Modifier in Asphalt

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Asphalt	Influence on Asphalt Properties								Contents%	Proposed content (%)	Proposed size (mm)	References
			Length (mm)	Width (mm)	AR	Type	Softening Point	Marshall Stability	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental-Friendly	Fatigue Resistance				
1	Plastic Waste	Shred	-	-	-	Asphalt Concrete Wearing Course (AC-WC)	-	↑	-	-	-	-	-	-	1, 2, 3	-	-	(Adhitya et al., 2020)
2	PET	Shred	-	-	-	-	-	↑	-	-	-	-	-	-	1-5@2	6.6	-	(Badejo et al., 2017)
3	PE and Waste Rubber Tires	Powder	-	-	-	waste plastic/rubber-modified asphalt (WPRMA)	-	-	-	-	↑	-	↑	-	2-10@2	-	-	(Zhang et al., 2021)
4	LDPE and PET Plastic Wastes	Shred	2-4	-	-	Hot Mixed Asphalt (HMA)	-	-	-	-	-	-	↑	-	15, 30	-	-	(Dalhat and Al-Abdul Wahhab, 2017)
5	LDPE	Powder	-	-	-	Porous Asphalt Mixture	-	↑	-	-	-	-	-	-	2-8@2	-	-	(Gusty et al., 2021)
6	PP, PET, HDPE and LDPE	Shred	2	-	-	hot bituminous mastics	-	↑	-	-	-	-	-	-	5-15@5	-	-	(Veropalumbo et al., 2021)
7	PET	Powder	-	-	-	Hot Mixed Asphalt (HMA)		↑	-	-	↑	-	-	-	1-5@1	-	-	(Naghawi, 2018)
8	waste PET and commercial waste plastic products MR6 and MR10	Shred	-	-	-	Asphalt Mixture	-	↑	-	↑	↑	-	-	↑	2-6@2	-	-	(Hall and White, 2021)
9	PE	Shred	-	-	-	Asphalt Mixture	↑	↑	-	↑	↑	↓	-	-	0.25, 1.5	-	-	(Pasetto et al., 2022)

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Asphalt Type	Influence on Asphalt Properties								Contents%	Proposed content (%)	Proposed size (mm)	References
			Length (mm)	Width (mm)	AR		Softening Point	Marshall Stability	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental-Friendly	Fatigue Resistance				
10	LDPE	Shred	-	-	-	Asphalt Mixture	-	-	-	↑	-	-	-	↑	2.5 (wet process)	-	-	(Abdalfattah et al., 2022a)
11	LDPE	Shred	-	-	-	Asphalt Mixture	-	-	-	↑	-	-	-	↑	10 (dry process)	-	-	(Abdalfattah et al., 2022a)
12	PET	Shred	2.36	-	-	Warm-mix asphalt	↑	-	↑	↑	-	-	-	↑	0.1-1.1@0.1	-	-	(A M Mosa et al., 2018)
13	PP	Shred	-	-	-	Warm-mix asphalt	↑	-	↑	↑	-	-	-	↑	2.5, 5.0, 7.5, 10, 12.5 and 15	-	-	(Akinpelu et al., 2013)

Table 2.7 Recycled Plastic Utilization as a Bitumen Modifier in Asphalt

NO.	Recycled Plastic type	Recycled Plastic Shape	Asphalt Type	Recycled Plastic Size			Influence on Asphalt Properties									Contents%	Propose d content (%)	Propose d size (mm)	References
				Lengt h (mm)	Widt h (mm)	AR	Softening Point	Marshall Stiffness Modulus	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental -Friendly	Fatigue Resistance	Ductility				
1	Rubber and PP	Powder	Hot Mixed Asphalt (HMA)	-	-	-	↑	-	-	-	-	↓	↑	-	-	20 (a blend of crumble rubber and PP powder by a ratio of 40:1)	-	-	(Yu et al., 2014)
2	PTP	Powder	Hot Mixed Asphalt (HMA)	-	-	-	↑	↑	↑	↑	↑	-	-	↑	-	2, 4, 6, 8, 10, 12	-	-	(El-Naga and Ragab, 2019)
3	PET	Powder	Hot Mixed Asphalt (HMA)	-	-	-	-	↑	-	-	↑	-	-	-	-	5, 7.5, 10, 12.5, 15	10	-	(Hake et al., 2020)
4	Tetra-Pak (TPA)	Shred	Hot Mixed Asphalt (HMA)	1-6	-	-	-	↑	-	-	-	-	--	-	-	1, 1.5	-	-	(Ajam, 2013)
5	PET and HDPE	Powder	Hot Mixed Asphalt (HMA)	-	-	-	-	↑	-	-	↑	-	-	-	-	2, 2.5, 3, 3.5, 4, 4.5	4	-	(Awad and Al Adday, 2017)
6	LDPE	Powder	Hot Mixed Asphalt (HMA	-	-	-	↑	↑	-	-	-	-	↑	-	-	3, 6, 9, 12	12	-	(Ali, 2021)
7	HDPE and LDPE	Powder	Hot Mixed Asphalt (HMA	-	-	-	-	↑	-	-	↑	-	↑	-	-	3, 3.5	3.5	-	(Yousuf et al., 2020)
8	PET	Powder	Asphalt Concrete Mixture	-	-	-	-	↑	↑	-	-	-	-	-	-	0.2,0.4,0.6	0.2	-	(Aziz and Shamshuddin, 2022)

NO.	Recycled Plastic type	Recycled Plastic Shape	Asphalt Type	Recycled Plastic Size			Influence on Asphalt Properties									Contents%	Proposed content (%)	Proposed size (mm)	References
				Length (mm)	Width (mm)	AR	Softening Point	Marshall Stiffness Modulus	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental -Friendly	Fatigue Resistance	Ductility				
9	PET	Shred	Hot and Warm mix asphalt (HMA and WMA)	-	-	-	↑	↑	-	-	-	-	-	-	↓	1- 17@2	-	-	(Tunde Akinleye et al., 2020)
10	HDPE	Seed	Asphalt Concrete-Wearing Course (AC-WC)	5	-	-	-	↑	-	-	↑	-	↑	-	-	0, 1, 2, 3, 4, 5, 6, 7	5	-	(Nawir and Mansur, 2021)
11	Disposable Food Pack (DFP)	Powder	Hot Mix Asphalt (HMA)	-	-	-	↑	↑	-		↑	-	-	-	-	1- 10@ 1	6.7	-	(Murana et al., 2021)
12	Water Plastic Bottle	Powder	Hot Mix Asphalt (HMA)	-	-	-	-	-	-	-	↑	-	↑	-	-	0.2, 0.5, 1.0, 5.0	0.2-0.5	-	(Abu Abdo and Khater, 2018)
13	PE	Shred	Hot Mix Asphalt (HMA)	-	-	-	-	-	↑	↑	-	-	-	-	-	2, 4, 6	-	-	(Amirkhanian, 2020)
14	LDPE, HDPE, and Crumb Rubber	Powder	-	-	-	-	-	-	↑	-	↑	-	-	-	-	2-10@2	-	-	(Khan et al., 2016)
15	PET	Powder	-	-	-	-	-	↑	-	-	-	-	-	-	-	2-10@2	8	-	(Mershed et al., 2015)
16	LDPE and Crumb rubber	Powder	Asphalt Concrete	-	-	-	-	↑	-	-	-	-	-	-	-	1-5@1	-	-	(Onyango et al., 2012)

NO.	Recycled Plastic type	Recycled Plastic Shape	Asphalt Type	Recycled Plastic Size			Influence on Asphalt Properties									Contents%	Proposed content (%)	Proposed size (mm)	References
				Length (mm)	Width (mm)	AR	Softening Point	Marshall Stiffness Modulus	Tensile Strength	Rutting Stiffness	Service Life	Water Susceptibility	E environmental -Friendly	Fatigue Resistance	Ductility				
17	PET	Shred	Hot Mix Asphalt (HMA)	-	-	-	-	↑	↑	↑	-	-	-	-	-	0.1-1@0.1	-	-	(Baghaee Moghaddam et al., 2014)
18	HDPE, LDPE, ethylene-vinyl acetate (EVA), acrylonitrile-butadiene-styrene (ABS), and crumb rubber	Granulated and in Powder	Hot Mix Asphalt (HMA)	-	-	-	↑	↑	-	-	-	-	-	-	-	5	-	-	(Costa et al., 2013)
19	Plastic waste	Powder	Hot Mix Asphalt (HMA)	-	-	-	↑	↑	-	↑	↑	-	-	↑	-	5-10@5	-	-	(Suaryana et al., 2018)
20	PET	powder	Asphalt Concrete	-	-	-	-	↑	-	-	-	-	-	-	-	3-7@1	-	-	(Machsus et al., 2020)
21	PP/PE	Powder	Asphalt Concrete	-	-	-	-	↑	-	-	-	-	-	↑	-	3,4	-	-	(Ballester-Ramos et al., 2023)

2.3.1 Influence of Recycled Plastics on Asphalt Properties

2.3.1.1 Softening Point

Results from previous studies show that adding recycled plastic to asphalt as a bitumen modifier increases the softening point of asphalt mixtures (Cong et al., 2019; Greg White and Connor Magee, 2019). This can be attributed to the binder's increased viscosity and softening temperature and the creation of significant elastic recovery.

2.3.1.2 Marshall Stability, Tensile Strength, and Flow Number

Adding recycled plastic to asphalt as a bitumen modifier, a binder modifier, or as an aggregate extender leads to a notable increase in the Marshall stability and tensile strength of asphalt mixtures (Abu Abdo and Jung, 2020; Abu Abdo and Khater, 2018; Alemu et al., 2023). Figure 2.2 shows the Marshall test results for stability values of HDPE and LDPE asphalt mixtures for both dry and wet processes. Figures 2.3 and 2.4 show the Marshall test results for flow numbers of HDPE and LDPE asphalt mixtures for both dry and wet processes, Figures 2.5 and 2.6 show the Marshall test results for stability value and flow number of PET, PVC, PTP and PP asphalt mixtures for dry and wet processes, respectively. In contrast to Marshall stability results, the Marshall flow numbers were not significantly affected by the use of recycled plastic. (Jin et al., 2020; Khurshid et al., 2019) reached the same conclusion that most likely reflects the increased variability associated with the Marshall flow test compared to the Marshall stability test and the impact of the aggregate skeleton on asphalt resistance to deformation.

2.3.1.3 Air Void Content

Figure 2.4 shows Marshall test results for air void content of HDPE and LDPE asphalt mixtures for both dry and wet processes. According to previous studies, adding recycled plastic to asphalt decreases the air-void ratio, since recycled plastic fills the void spaces between asphalt mixture particles (Köfteci, 2016).

2.3.1.4 Service Life and Environmental-Friendliness

Adding recycled plastic to asphalt increases the long-time service life of asphalt mixtures and improves their performance (Tapkin, 2008). Based on studies such as (A. M. Mosa et al., 2018; Zhang et al., 2021), adding recycled plastic to asphalt also reduces energy consumption, so it is an environmentally-friendly approach.

2.3.1.5 Water Susceptibility

Adding recycled plastic to asphalt decreases water susceptibility, possibly ascribed to the asphalt's lower air void content that lessens moisture damage to the mixture (Almeida et al., 2019).

2.3.1.6 Fatigue Resistance

Adding recycled plastic to asphalt leads to an increase in asphalt-mixture fatigue resistance as a result of improving the recycled plastic-bitumen-phase interaction (Dalen et al., 2017; Dehghan and Modarres, 2017; Mashaan et al., 2021), a result of the recycled plastic’s chemical properties. The creation of molecular structures of recycled plastic bitumen with improved tensile strength and elastic response, which in turn increase fatigue resistance, substantially impacted the strength of asphalt (Singh and Kumar, 2019), although studies in this area are rare.

2.3.1.7 Rutting Stiffness

To understand rutting resistance, it is crucial to investigate the effects of the modified asphalt since rutting stiffness is related to an asphalt binder's sensitivity to stresses and temperatures when modified binders are used (Onyango et al., 2012). Adding recycled plastic to asphalt increases asphalt-mixture rutting resistance (Mansourian et al., 2019; Neves and Freire, 2022) due to the clustering of molecules and their connections.

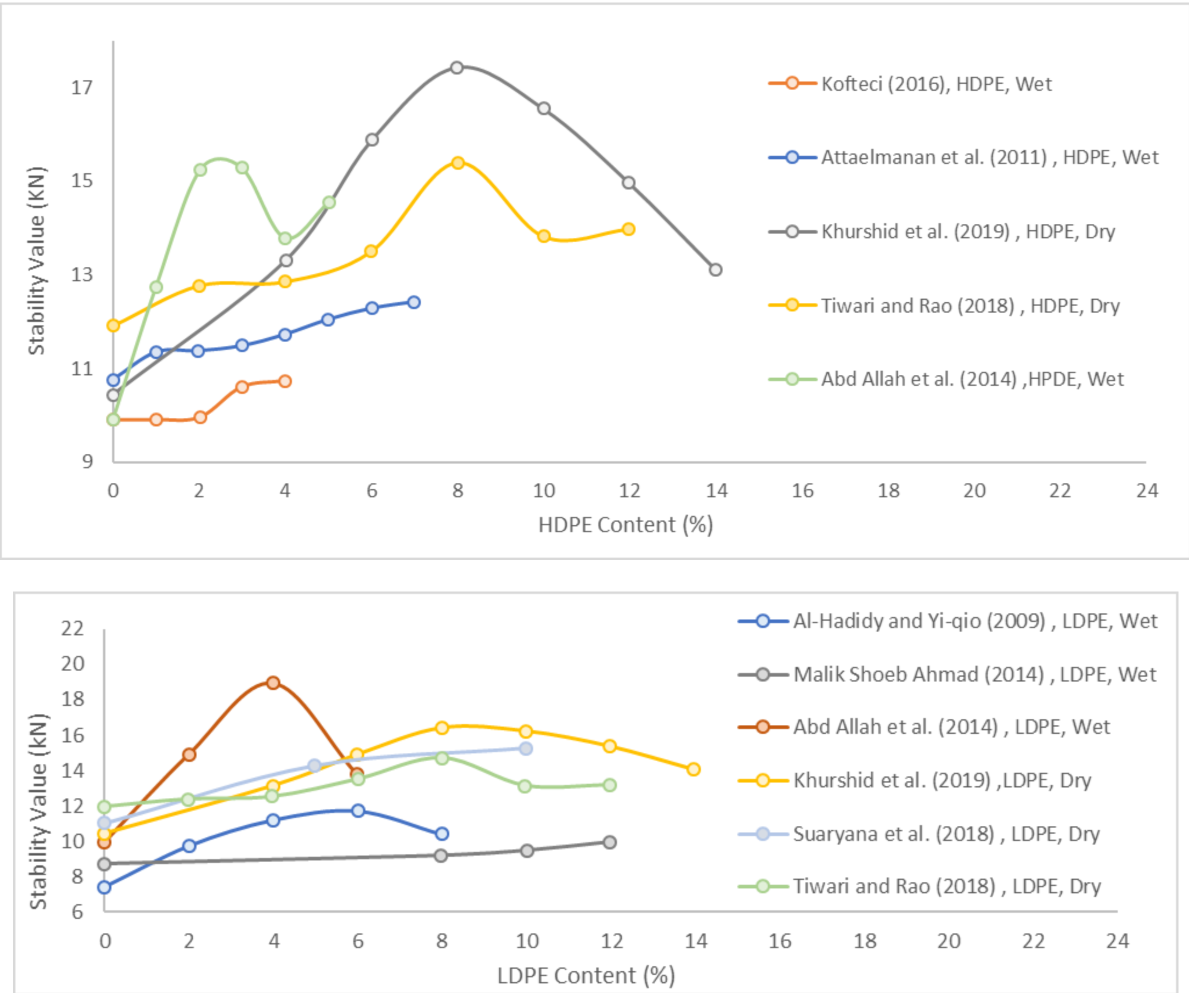

Figure 2.2 Marshall test results for stability value of HDPE and LDPE asphalt mixtures. (Dry = dry process, Wet = wet process)

Data Source and Adapted from (Al-Hadidy and Yi-qiu, 2009; Attaelmanan et al., 2011; Heydari et al., 2021; Khurshid et al., 2019; Köfteci, 2016; Malik Shoeb Ahmad, 2014; Mohamady Abd-Allah et al., 2014; Suaryana et al., 2018; Tiwari and Rao, 2018)

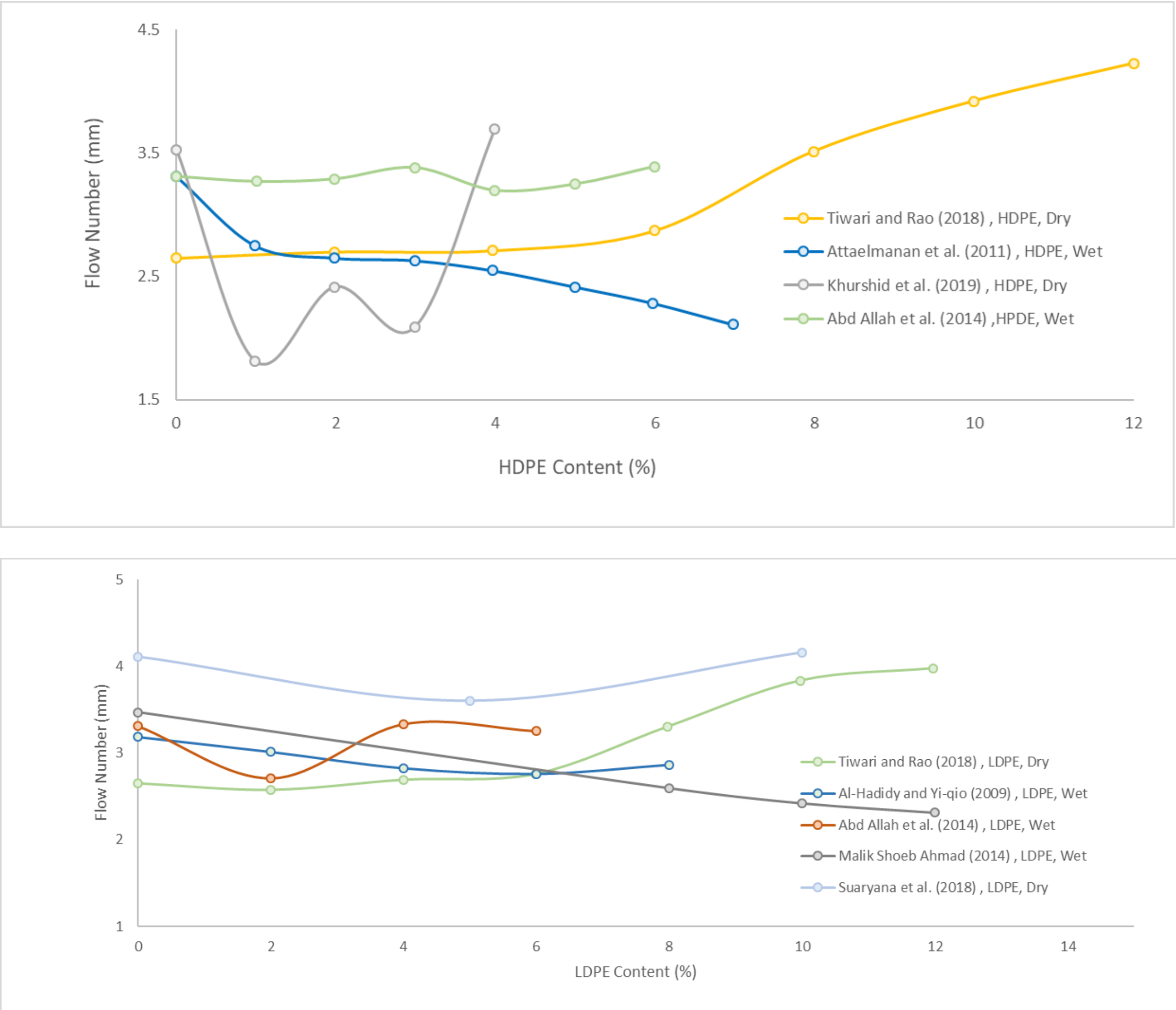

Figure 2.3 Marshall test results for Flow number of HDPE and LDPE asphalt mixtures. (Dry = dry process, Wet = wet process)

Data Source and Adapted from (Al-Hadidy and Yi-qiu, 2009; Attaelmanan et al., 2011; Heydari et al., 2021; Khurshid et al., 2019; Malik Shoeb Ahmad, 2014; Mohamady Abd-Allah et al., 2014; Suaryana et al., 2018; Tiwari and Rao, 2018)

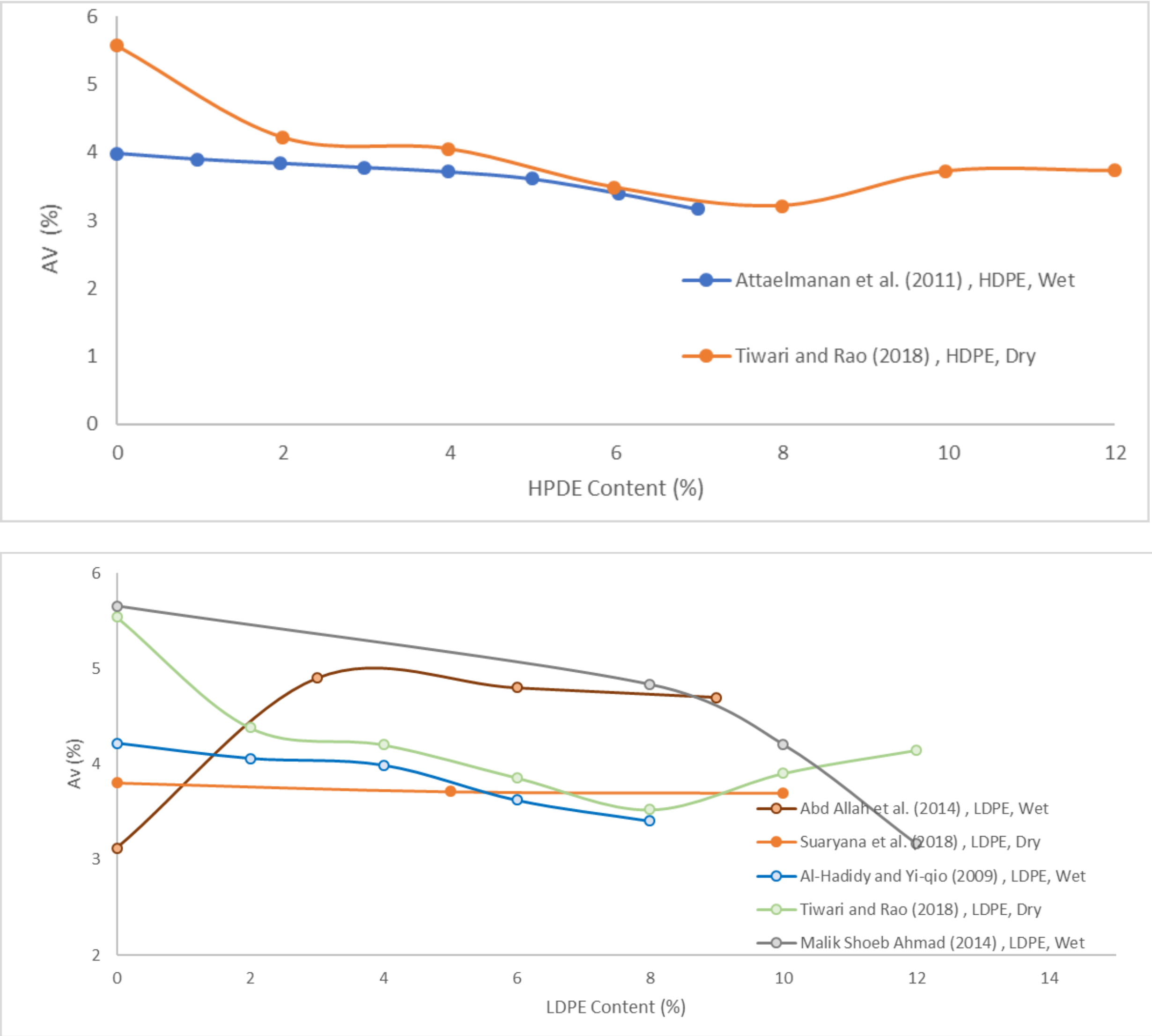

Figure 2.4 Marshall test results for Air Void content of HDPE and LDPE asphalt mixtures. (Dry = dry process, Wet = wet process)

Data Source and Adapted from (Al-Hadidy and Yi-qiu, 2009; Attaelmanan et al., 2011; Heydari et al., 2021; Khurshid et al., 2019; Malik Shoeb Ahmad, 2014; Mohamady Abd-Allah et al., 2014; Suaryana et al., 2018; Tiwari and Rao, 2018)

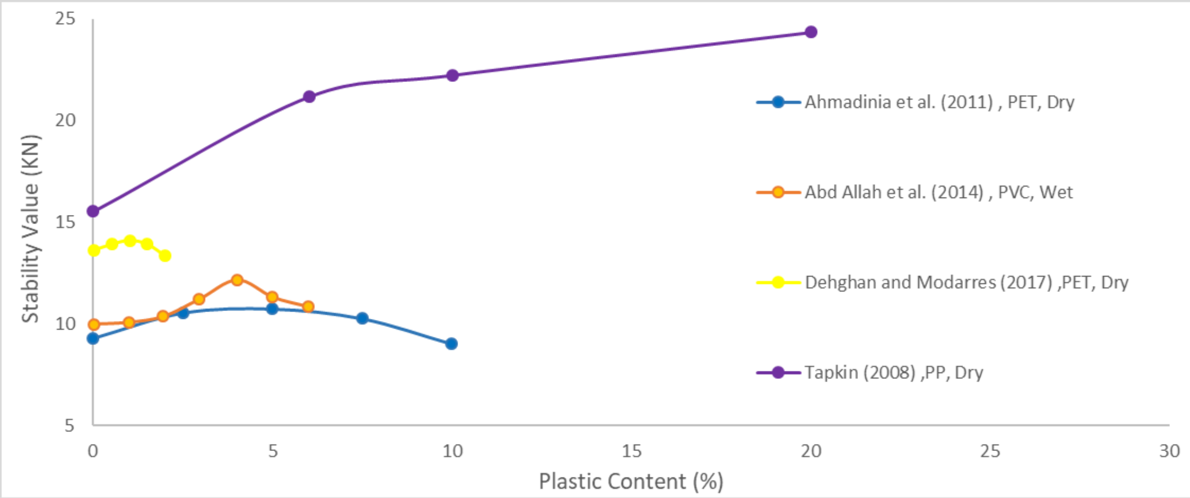

Figure 2.5 Marshall test results for stability value of PET, PVC and PP asphalt mixtures. (Dry = dry process, Wet = wet process)

Data Source and Adapted from (Ahmadinia et al., 2011; Dehghan and Modarres, 2017; Heydari et al., 2021; Mohamady Abd-Allah et al., 2014; Tapkin, 2008)

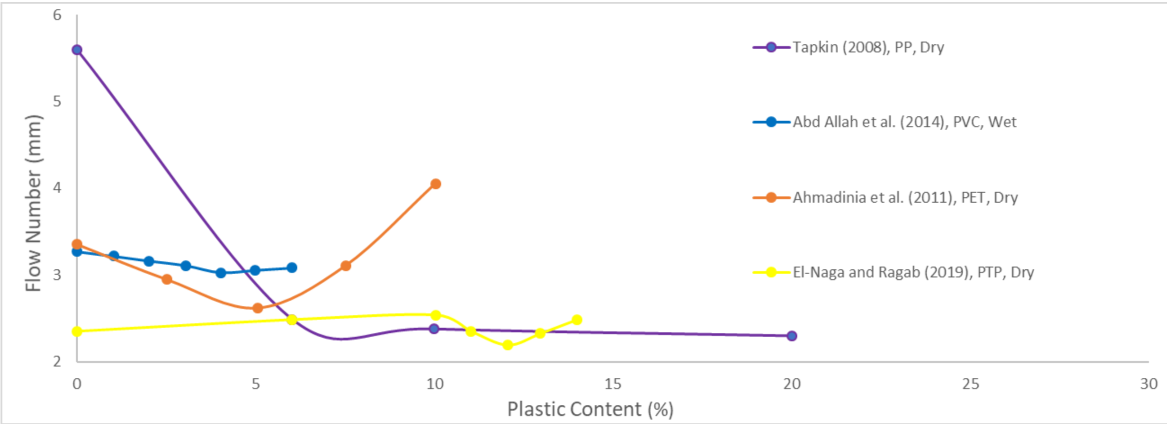

Figure 2.6 Marshall test results for Flow number of PET, PVC and PP asphalt mixtures. (Dry = dry process, Wet = wet process)

Data Source and Adapted from (Ahmadinia et al., 2011; El-Naga and Ragab, 2019; Heydari et al., 2021; Mohamady Abd-Allah et al., 2014; Tapkin, 2008)

A wet and a dry process are two ways that recycled plastic can be used in asphalt mixtures, with the former technique more common than the latter, although it requires specialized machinery. In contrast, any asphalt factory can use the dry process without requiring significant changes (Duarte and Faxina, 2021). As previously indicated, in using the dry process, recycled plastic can be added to an asphalt mixture as an additive, an aggregate replacement, or a partial replacement for an asphalt binder. The dry method, integrating recycled plastic into heated aggregates before adding asphalt, is usually suitable for producing all forms of asphalt mixtures. Plastics perform several different roles in this process, including coating or particle or aggregate replacement, depending on the size and properties of the plastics used (Duarte and Faxina, 2021; Ma et al., 2021). While plastics with low melting points could provide a thin film to cover the aggregates, high melting point plastics are more typically used to replace aggregates (Hassani et al., 2005; Ma et al., 2021). The dry process is typically used with rigid, hard plastics such as HDPE and PET with high melting temperatures (Wu and Montalvo, 2021). The wet process, more appropriate for recycled plastics with low melting points like LDPE and PP, involves immediately adding recycled plastic as a modifier into the asphalt and mixing it with aggregate (Wu and Montalvo, 2021). Few studies have concentrated on wet-asphalt modification utilizing recycled plastic. Table 2.8 summarizes recently performed studies of the characteristics of asphalt modified with recycled plastic using both dry and wet processes. Based on the literature review, adding recycled plastic can significantly improve rutting resistance, fatigue cracking resistance, and cracking at both low and high temperatures of asphalt mixtures. An analysis comparing the dry and wet methods for utilizing waste polymers in modified asphalt mixtures was conducted by (Ranieri et al., 2017; Wu and Montalvo, 2021), and it was found that all blends except for the HDPE-modified mixture showed similar levels of moisture resistance, volumetric properties, and stiffness for both dry and wet methods.

Table 2.8 Summary of asphalt properties modified with recycled plastic through dry and wet process

Type of Recycled Plastic	Process Type	Environmental concerns	Low-temperature cracking resistance	Rutting resistance	Fatigue cracking resistance	References
PET	Dry	-	↓	↑	↑	(Hassani et al., 2005; Ma et al., 2021)
PVC	Dry	-	↓	↑	↑	(Hassani et al., 2005; Ma et al., 2021)
PP	Dry	-	↓	↑	↑	(Mashaan et al., 2021)
PET	Wet	-	-	↑	↑	(Duarte and Faxina, 2021; Ma et al., 2021)
PVC	Wet	-	↓	-	-	(Köfteci et al., 2014)
PVC	Wet	-	-	↑	-	(Arabani and Yousefpour Taleghani, 2017; Ziari et al., 2019)

2.4 Review of Recycled Plastic Utilization in The Concrete Infrastructure Applications

Recycling plastic waste into cement or concrete mixtures appears to be a superior alternative for plastic-waste disposal (Kamaruddin et al., 2017) because it exhibits economic and ecological advantages and can replace a considerable volume of aggregate in concrete mixtures.

Tables 2.9-2.12 describe and summarize recent progress in developing concrete mixtures incorporating recycled plastic during concrete manufacturing. Recycled plastics have often been used as fine or coarse concrete materials. Although using recycled plastic in concrete is advantageous for the environment, its engineering properties fundamentally differ from natural aggregates (as shown in Tables 2.9-2.12). It is also important to note that a recycled plastic's pre-treatment can affect the properties of concrete containing it, and such treatment may significantly impact how well plastic aggregates and cement paste bind to one another (Saxena et al., 2018, 2016). Concrete, with its relatively extended service life, can be a suitable application for recycled plastic (Belmokaddem et al., 2020). This section overviews the many experiments carried out to examine the impact of adding plastic to concrete. Also described are earlier studies in which an attempt was made to determine the feasibility and potential replacement percentages of plastic that can be utilized in concrete.

According to the literature, concrete containing recycled plastic aggregate can effectively produce lightweight concrete because concrete with varying percentages of recycled plastic aggregate typically has a lower density than fresh concrete (Habib and Alom, 2017). Further study is necessary to fully comprehend the durability aspects of concrete that includes recycled plastic aggregate. Concrete with recycled plastic aggregate has an improved elasticity modulus than new concrete (Habib and Alom, 2017). Concrete can contain recycled plastic waste up to a specific percentage volume without significantly changing its properties (Saxena et al., 2016), but the inclusion of plastic waste influences its workability. An increase in plastic waste in concrete resulted in a drop in the compaction factor and the slump value (Saxena et al., 2018). Several investigations show that, within specific limits, the strength of concrete containing plastic waste was comparable to that of reference concrete, and up to a certain point, concrete made from plastic waste has durability characteristics similar to reference concrete (Saxena et al., 2016). Using plastic waste in a concrete mixture has been a major success in producing environmentally friendly, long-lasting concrete. Some studies' results have demonstrated that recycled plastic in fiber form enhanced mechanical performance, but recycled plastic as coarse aggregate impaired concrete performance because of poor bonding (Kishore and Gupta, 2019; Moreno et al., 2016).

Tables 2.9-2.12, show that most studies have utilized PET as a recycled plastic in concrete, with PET waste-derived fibers found suitable for use as reinforcement in concrete (Ahmad et al., 2022; Moreno et al., 2016). It was observed that PET fiber-reinforced concrete (PFRC) exhibited greater compressive strength than regular concrete (Moreno et al., 2016). For higher aspect ratios, the increase in compressive strength of PFRC was higher, while the compressive strength of PFRC was more increased for larger aspect ratios. The replacement of fine aggregate with PET fibers gradually increases the flexural strength of the specimens as the replacement percentage increases. Concrete's tensile splitting strength can be improved by using PET fiber, and the strength of concrete containing PET fibers is increased compared to regular concrete at all ages. It was concluded that including PET fiber can improve concrete's bending strength and splitting tensile strength (Moreno et al., 2016). The shear strength of the mix increases up to a specific amount of PET fiber, after which it decreases (Moreno et al., 2016). The inclusion of PET fibers results in a definite increase in the modulus of elasticity of concrete.

Table 2.9 Recycled Plastic Utilization as Coarse Aggregate in Concrete

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Concrete Type	Influence on Concrete Properties											Contents%	Proposed content (%)	Proposed size (mm)	References
							Fresh Concrete properties			Mechanical Properties				Durability Properties							
			Length (mm)	Width (mm)	AR		Workability	Fresh Density	Air Content	Compressive Strength	Indirect Tensile Strength	Flexural Strength	Static Modulus of Elasticity	Water Absorption	Water Sorptivity	Abrasion Resistance	Drying Shrinkage				
1	HDPE	Fiber	-	-	-	Fiber Reinforced Concrete (FRC)	-	-	-	↑	↑	↑	-	-	-	-	-	0-6@0.5	-	-	(Malagavelli and Rao Paturu, 2011)
2	E-plastic	Fiber	-	-	-	Normal Concrete	-	-	-	↓	-	-	-	-	↓	-	-	4-24@4	-	-	(Lakshmi and Nagan, 2011)
3	Recycled PET and virgin polypropylene	Fiber	0.12-2	-	-	Normal Concrete	-	-	-	↑	↑	↑	-	-	-	-	-	1	-	-	(Fraternali et al., 2011)
4	PP	Shred Fiber	60	3	-	Normal Concrete	-	-	-	↑	-	-	-		-	-	-	0.3-1.2@0.3	0.6	-	(Bhogayata and Arora, 2019, 2018)
5	PP	Flakes	-	-	-	Normal Concrete	-	-	-	↑	↑	↑	-	-	-	-	-	0-15@5	-	-	(Rai et al., 2012)
6	Plastic bags	Shred	-	-	-	Normal Concrete	-	-	-	-	↑	-	-	-	-	-	-	1	-	-	(Raghatate Atul, 2012)
7	PET	Fiber	-	-	-	Normal Concrete	-	-	-	↑	-	↑	-	-	-	-		1, 2, 4, 6	-	-	(Manjunath, 2016)
8	PET	Shred	-	-	-	Normal Concrete		--	-	↓	↓	↓	↓	↓	-	-	-	7.5, 15	-	-	(Ferreira et al., 2012)
9	PET	Shred Fiber	2	1	-	Normal Concrete	-	-	-	↑	-	-	-	-	-	-	-	0.5-1.5@0.5	0.5	-	(Bhogayata et al., 2015)
10	Waste Plastic fiber	Fiber	-	-	30-110@20	Fiber Reinforced Concrete (FRC)	-	-	-	↑	↑	↑	-	-	-	-	-	0.5	AR=50	-	(Prahallada M C and Prakash K, 2013)
11	Pulverized plastic	Granular	1	-	-	Normal Concrete	-	-	-	↑	↑	↑	-	-	-	-	-	25-100@25	25	-	(P. Suganthy et al., 2013)
12	PET	Pellet	-	-	-	Normal Concrete	-	-	-	↑	↑	↑	-	-	-	-	-	5, 10, 15	-	-	(Saikia and De Brito, 2013)
13	PET	Circular Fiber	-	5	-	Normal Concrete	-	-	-	↑	↑	↑	-	-	-	↑	-	1	-	-	(Foti, 2013)
		Strip		-																	
14	Plastic waste	Fiber	-	-	-	Normal Concrete	↓	↓	-	↓	-	-	-	-	-	-	-	25-100@25	33	-	(Osei et al., 2014)
15	Polythene Bags	Shred	-	-	-	Normal Concrete	↓	-	-	↓	-	↑	-	-	-	-	-	2,5,7	-	-	(Usman et al., 2018)
16	E-plastic	Angular and Triangular shred	-	-	-	Normal Concrete	-	-	-	↓	↓	-	-	↑	-	-	-	5-15@5	-	-	(Akram, 2015)
17	PP and PET	Fiber	-	-	-	Normal Concrete		-	-	↓	-	↑	-	↑	-	↑	-	0-50@10	-	-	(Sambhaji, 2016)

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Concrete Type	Influence on Concrete Properties											Contents%	Proposed content (%)	Proposed size (mm)	References
							Fresh Concrete properties			Mechanical Properties				Durability Properties							
			Length (mm)	Width (mm)	AR		Workability	Fresh Density	Air Content	Compressive Strength	Indirect Tensile Strength	Flexural Strength	Static Modulus of Elasticity	Water Absorption	Water Sorptivity	Abrasion Resistance	Drying Shrinkage				
18	PET	Fiber	10	2	-	Self-Compacting Concrete	-	-	-	↑	↑	↑	-	-	-	-	-	0-2@0.25	-	-	(Al-Hadithi and Hilal, 2016)
19	PET	Shred	-	-	-	Normal Concrete	↑	-	-	↑	-	-	-	-	-	-	-	20-50@10	-	-	(Islam et al., 2016)
20	E-plastic	Fiber	-	-	-	Polymer Concrete	-	-	-	↓	↓	↓	-	-	-	-	-	5-25@5	-	-	(Bulut and Şahin, 2017)
21	Metallic plastic	Fiber	-	-	-	Normal Concrete	-	-	-	-	-	-	-	↑	-	↑	-	0.5-2@0.5	-	-	(Bhogayata and Arora, 2018)
22	PET	Shred Fiber	-	-	-	Normal Concrete	↓	↓	-	↑	↑	↑	↑	↑	↓	↑	↑	↑	20	-	(Abu-Saleem et al., 2021)
23	HDPE	Shred Fiber	20	-	-	Normal Concrete	↓	↓	-	↑	↑	↑	↑	↑	↑	↑	-	10-30@10	-	-	(Abu-Saleem et al., 2021)
24	PET	Shred Fiber	7	-	-	Normal Concrete	↓	-	-	↑	↑	↑	↑	-	-	-	-	5-15@5	5	-	(Rahmani et al., 2013)
25	PET	d Shredded fine flaky	-	-	-	Normal Concrete	-	↓	-	↑	↑	↑	↑	-	-	↑	-	5-15@5	-	-	(Saikia and De Brito, 2014)
26	PET	Shred Fiber	7	-	-	Normal Concrete	-	-	-	-	-	-	-	-	-	↑	-	5-15@5	-	-	(Janfeshan Araghi et al., 2015)
27	PET and waste glass	Shred	16	6	-	Normal Concrete		-	-	↓	↓	-	-	↑		-	-	5-25@5	10	-	(Belmokaddem et al., 2020)
28	PP	Shred Fiber	-	-	-	Normal Concrete	↓	↓	-	↑	↑	↑	↑	↑	↓	↑	-	10-30@10	20	-	(Abu-Saleem et al., 2021)

Table 2.10 Recycled Plastic Utilization as fine Aggregate (Sand) in Concrete

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Concrete Type	Influence on Concrete Properties											Contents%	Proposed content (%)	Proposed size (mm)	References
							Fresh Concrete properties			Mechanical Properties				Durability Properties							
			Length (mm)	Width (mm)	AR		Workability	Fresh Density	Air Content	Compressive Strength	Indirect Tensile Strength	Flexural Strength	Static Modulus of Elasticity	Water Absorption	Water Sorptivity	Abrasion Resistance	Drying Shrinkage				
1	80% Polyethylene and 20% Polystyrene	shred	-	-	-	Normal Concrete	↓	-	-	-	-	-	-	-	-	-	-	10-20@5	-	-	(Ismail and AL-Hashmi, 2008)
2	PET	Fiber	1.14	0.26	-	Normal Concrete	↑	-	-	↓	-	↑	↓	-	-	-	-	10,20	-	-	(Albano et al., 2009)
3	PET	Fiber	0.1-5	-	-	Normal Concrete	-	-	-	↓	↓	↑	-	-	-	-	-	5	-	-	(Frigione, 2010)
4	PET	Fiber	-	-	-	Normal Concrete	-	-	-	↓	↓	↓	-	-	-	-	-	2-6@2	4	-	(Mahesh et al., 2016)
5	Waste Plastic bag	Shred	-	-	-	Normal Concrete	↑	↑	-	-	-	-	-	-	-	-		10-30@10	-	-	Ghernouti et al (2011)
6	PET	shred	-	-	-	Normal Concrete	-	↑	-	↓	↓	↓	↑	-	-	-	-	5, 10, 20	10	-	Hossain et al (2016)
7	PET	Fiber	-	-	-	Normal Concrete	-	↑	-	-	-	-	-	-	-	-	-	5-20@5	10	-	(Vali and Asadi, 2017)

Table 2.11 Recycled Plastic Utilization as Cement Alternative in Concrete

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Concrete Type	Influence on Concrete Properties											Contents%	Proposed content (%)	Proposed size (mm)	References
							Fresh Concrete properties			Mechanical Properties				Durability Properties							
			Length (mm)	Width (mm)	AR		Workability	Fresh Density	Air Content	Compressive Strength	Indirect Tensile Strength	Flexural Strength	Static Modulus of Elasticity	Water Absorption	Water Sorptivity	Abrasion Resistance	Drying Shrinkage				
1	Plastic Bags	Fiber	-	-	-	Normal Concrete	↓	-	-	↑	-	-	-	-	-	-	-	0-1@0.25	-	-	(Aamir Gour et al., 2020)

Table 2.12 Recycled Plastic Utilization as Additive in Concrete

NO.	Recycled Plastic type	Recycled Plastic Shape	Recycled Plastic Size			Concrete Type	Influence on Concrete Properties											Contents%	Proposed content (%)	Proposed size (mm)	References
							Fresh Concrete properties			Mechanical Properties				Durability Properties							
			Length (mm)	Width (mm)	AR		Workability	Fresh Density	Air Content	Compressive Strength	Indirect Tensile Strength	Flexural Strength	Static Modulus of Elasticity	Water Absorption	Water Sorptivity	Abrasion Resistance	Thermal Conductivity				
1	HDPE, LDPE, PP and PET	Fiber	-	-	-	Low Thermal Conductivity Concrete	↓	↓	-	-	↓	↓	-	-	-	-	↓	HDPE, and LDPE (5), PP (10), PET (50)	-	-	(Poonyakan et al., 2018)

2.4.1 Influence of Recycled Plastic on Concrete Mechanical Properties

Compressive strength, flexural strength, and splitting tensile strength of concrete containing recycled plastic demonstrate that the strength of concrete increases in general, but it is not effectively increased when too much-recycled plastic is added to mixtures (Usman et al., 2018). A small amount of plastic waste incorporated into concrete resulted in little or no increase in tensile strength, and with increasing plastic aggregate content, there was a decrease in compressive strength development (Babafemi et al., 2018). Some studies, however, have found that using low levels of recycled plastic increases compressive strength. An increase in the incorporation of aggregate plastic fibers (content and length) reduces compressive strength due to the subsequent increase in air content (Saxena et al., 2018). The elastic modulus exhibits a linear decline with the increase in plastic aggregate content, but the decrease in elastic modulus is comparatively less pronounced than the observed reduction in compressive strength (Manjunath, 2016).

2.4.1.1 Compressive Strength

Various researchers have reported on the compressive strength of concrete containing various percentages of recycled plastic incorporated as coarse and fine aggregates, as listed in Tables 2.9-2.12 and Figure 2.7. The compressive strength generally decreased with more recycled plastic in concrete (Lakshmi and Nagan, 2011). Three distinct mechanisms have been suggested to elucidate this decline in compressive strength (Panchal et al., 2020):

(1) The strength and stiffness of the recycled plastic aggregates are inferior to those of natural aggregates, rendering them prone to damage propagation and the formation of stress concentration zones.
(2) There is an interfacial transition zone between waste plastic aggregate and cement paste that exhibits low strength, thereby contributing to the overall weakness of the material, or perhaps there is just an inferior bond
(3) Incorporating recycled plastic aggregates in the mixture leads to an elevation of air content, further contributing to the material's compromised state.

Contrary to the general trend, certain authors have reported a different pattern in which adding recycled plastic to concrete increased compressive strength (Panchal et al., 2020) (Mahmoud Hama, 2021). However, it should be noted that in those studies, increasing the replacement volume further decreased compressive strength. This phenomenon was ascribed to the specific source of plastics utilized in their investigation (Gesoglu et al., 2017; Jacob-Vaillancourt and Sorelli, 2018). Similar outcomes were observed when recycled plastic was employed as a fiber in concrete. Concrete's lower compressive strength results from adding metalized plastic waste (MPW) fibers, increasing air voids (Babafemi et al., 2018). A weak bond is also established by the untreated plastic fiber surfaces, also leading to the weakening of the concrete strength.

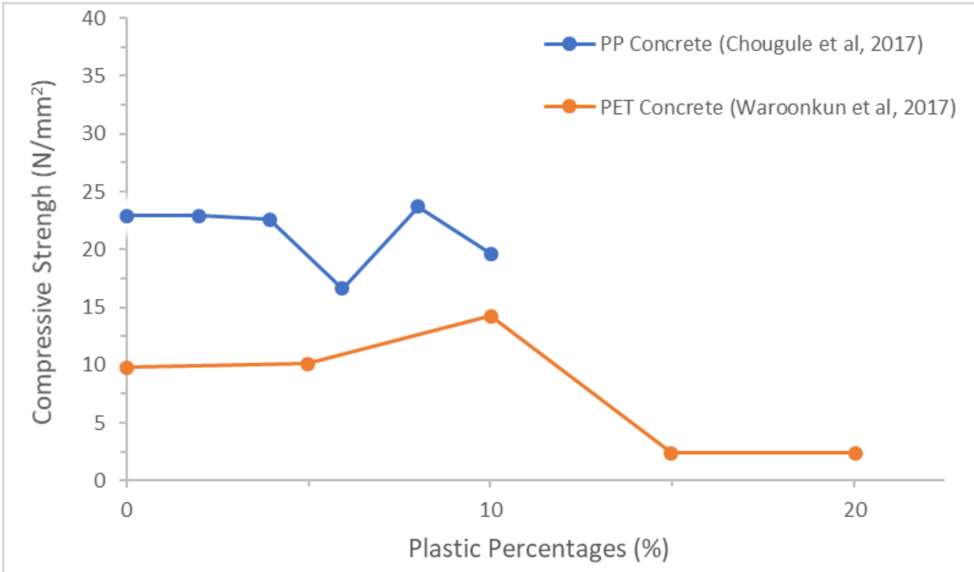

Figure 2.7 Variation of compressive strength (28-day) of construction materials with varying plastic replacement percentages

Data Source and Adapted from (Chougule et al., 2017; Waroonkun et al., 2017; Zulkernain et al., 2021)

2.4.1.2 Elastic Modulus

The elastic modulus of concrete tends to decrease progressively with an increase in the proportion of recycled plastic aggregate replacement in the mixture (Hannawi et al., 2010a), but it has been noted that the decrease in elastic modulus is relatively less pronounced than the compressive strength reduction (Gesoglu et al., 2017; Jacob-Vaillancourt and Sorelli, 2018).

2.4.1.3 Tensile and Flexural Properties

A progressive reduction in flexural and splitting tensile strengths was observed as the percentage of recycled plastic aggregates increased. Some studies also observed a decline in flexural or bending strength (Akçaözoğlu et al., 2010). As the proportion of recycled plastic replacement in concrete increased, the splitting and flexural strengths of concrete also gradually decreased, primarily due to the weak bond between the cement matrix and the aggregates, analogous to loss of compressive strength reduction resulting from the inclusion of waste plastic aggregates (Hannawi et al., 2013). Including an adequate quantity of recycled plastic aggregate can improve the concrete's flexural and splitting tensile strength(Hameed and Ahmed, 2019). With more than 20% of natural aggregate replaced with waste plastic particles, concrete's flexural and splitting tensile strength decreased. By reducing the water-cement ratio reduction in the concrete mix, the splitting strength of concrete can be improved (Zulkernain et al., 2021), so to achieve optimal performance aligned with design requirements, suitable plastic types must be selected for use in concrete.

The results of the flexural and splitting tensile strength of concrete with different types and quantities of plastic aggregate are shown in Figures 2.8 and 2.9, respectively. These results demonstrate that most concrete mixes exhibit a decline in flexural strength after the introduction of plastic waste as aggregate, and earlier studies have also demonstrated that integrating plastic waste as aggregate harms the splitting tensile strength of concrete, resulting in a significant reduction in the overall splitting tensile strength.

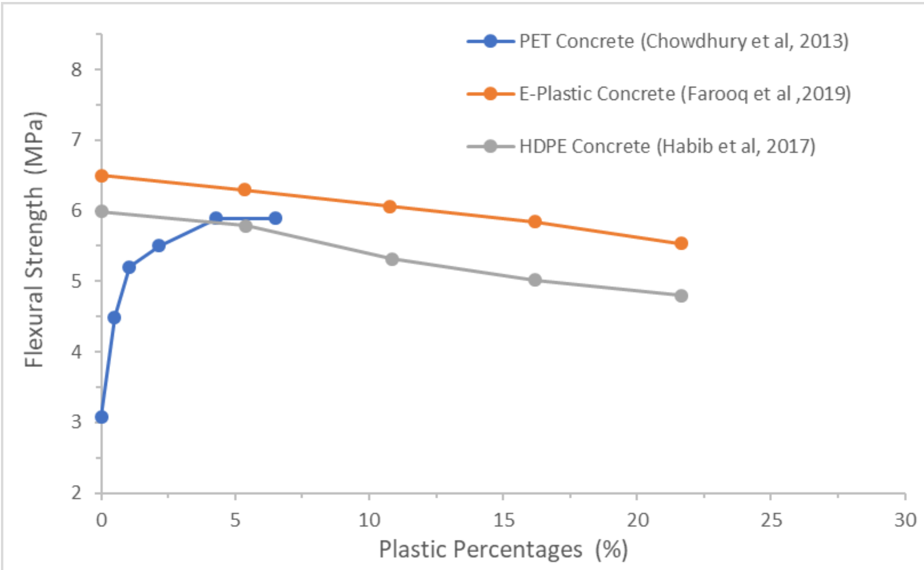

Figure 2.8 Flexural strength (28-day) of concrete variation with substitution level of plastic aggregates

Data Source and Adapted from (Chowdhury et al., 2013; Farooq, 2019; Habib and Alom, 2017; Sharma and Bansal, 2016; Zulkernain et al., 2021)

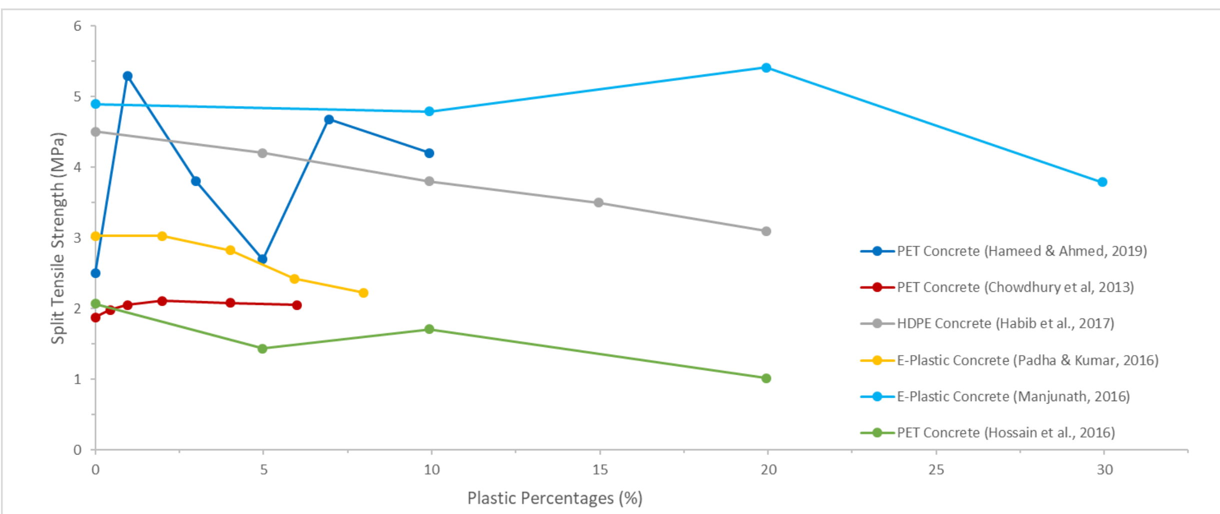

Figure 2.9 28-day split tensile strength variation with various replacement ratios and types of plastic aggregates

Data Source and Adapted from (Chowdhury et al., 2013; Habib and Alom, 2017; Hameed and Ahmed, 2019; Hossain et al., 2016a; Manjunath, 2016; Ravi Kumar, 2016; Zulkernain et al., 2021)

2.4.2 Influence of Recycled Plastic on Concrete Durability Properties

Because fluids and gases can cause steel corrosion in concrete, their permeability impacts concrete durability (Jiang et al., 2021; Lakshmi and Nagan, 2011), so choosing the right concrete materials is essential for achieving increased durability. While studies on the durability properties of concrete containing recycled plastic are rare in the literature, those who have investigated those properties have sometimes concluded that adding recycled plastic can enhance concrete durability properties. Previous studies have shown that recycled plastic aggregates are not as durable as natural aggregates, although some investigations have shown that durability can be increased by modifying the plastic's characteristics or adding additional specific components to the concrete.

2.4.2.1 Shrinkage

Conflicting results have been published concerning the impact of recycled plastic aggregates on concrete shrinkage. According to some studies, free and drying shrinkage increases with the amount of waste-recycled plastics in the mixture (Akçaözoğlu et al., 2010). This trend is to be expected since shrinkage is influenced by two material characteristics: the stiffness and composition of the aggregate and the shrinkage of cement pastes. Aggregates impose internal constraints on the shrinkage because they do not shrink, and it is anticipated that using recycled plastic would increase shrinkage because it is typically more compliant than natural aggregates (Hossain et al., 2016b) (El-Naga and Ragab, 2019). Because plastic aggregates have a lower elastic modulus than conventional aggregates, their higher shrinkage value in concrete can be anticipated.

However, it has been observed that using recycled plastic particles reduces concrete's drying shrinkage because waste plastic aggregates are impermeable, thereby reducing the quantity of water they absorb and leaving more free water for cement hydration (El-Naga and Ragab, 2019). As a result, there will be a decrease in drying shrinkage because the capillary tensile force that causes drying shrinkage is generated by the concrete's water loss. Despite frequent reports to the contrary, it appears that including recycled waste plastic reduces restrained shrinkage cracking while increasing free shrinkage (Sharma and Bansal, 2016; Zulkernain et al., 2021).

2.4.2.2 Water Absorption

Some previous studies (as depicted in Figure 2.10) have concluded that water absorption rises with the proportion of plastic aggregate material (Hannawi et al., 2010b) (El-Naga and Ragab, 2019), and concrete with 15% coarse recycled plastic absorbed water at a rate about 100% higher than that of reference concrete. Replacing 50% of sand with plastic aggregates resulted in a notable increase, about 117%, in water absorption in concrete. This considerable increase in water absorption can be attributed to the porosity created by the plastic particles (Coppola et al., 2018)(Babafemi et al., 2018)

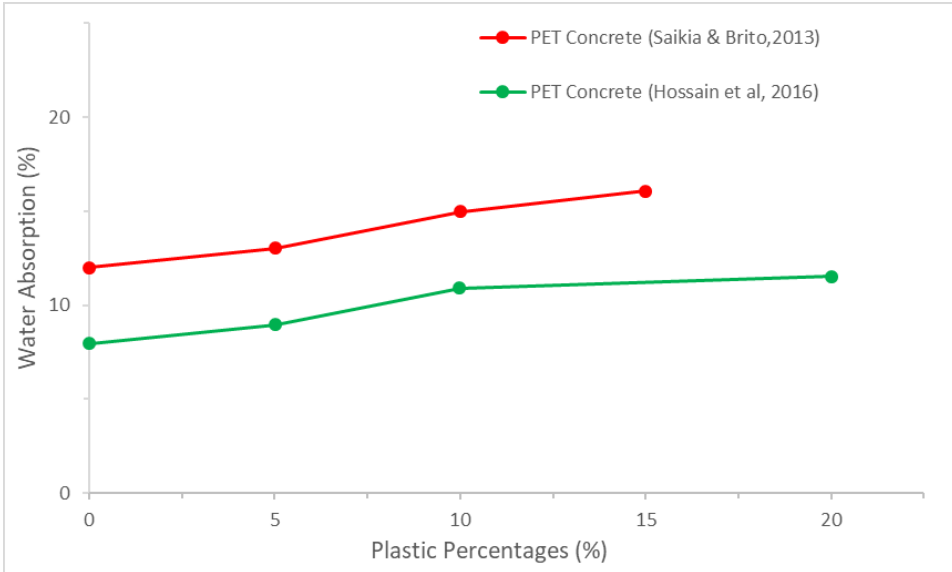

Figure 2.10 Water absorption of concrete produced with plastic waste

Data Source and Adapted from (Hossain et al., 2016a; Saikia and De Brito, 2013; Sharma and Bansal, 2016; Zulkernain et al., 2021)

2.4.2.3 Other Durability Properties

Little research has been done on other durability characteristics of recycled plastics in concrete. The use of recycled plastic aggregates in place of natural aggregates has proven to dramatically reduce the thermal conductivity of concrete (Mustakiza Zakaria et al., 2018; Rai et al., 2020), and thermal conductivity has been found to be proportional to dry density in general (De la Colina Martínez et al., 2019; Farooq, 2019).

2.4.3 Influence of Recycled Plastics on Fresh Concrete Properties

Workability, air void content, and flowability of fresh concrete are considered to be its most crucial properties. The original properties of concrete may be drastically changed when recycled plastics are used as aggregate in a concrete mix.

2.4.3.1 Workability

The workability of concrete as the content of fine recycled waste plastic aggregate increases can either improve or deteriorate based on factors such as particle shape, size, water-cement ratio, and the quantity of cement paste (Kishore and Gupta, 2019). In one study, adding up to 30% of recycled plastic aggregate decreased the workability, slump, and compressive strength of concrete (Aldahdooh et al., 2018). However, other researchers have observed that as coarse recycled plastic aggregate percentage rises by up to 50%, so does the workability of the concrete, with workability declining above this ratio.

2.4.3.2 Air Void Content

According to the literature, the air content in concrete is increased by adding plastic aggregates, with the plastic particles' irregular shapes a possible factor in the concrete's higher air content for an amount of effective fine plastic aggregate up to 20%. The immiscibility of plastic fine aggregate and natural sand may also be a primary reason for the increase in concrete air content(Sharma and Bansal, 2016; Zulkernain et al., 2021). The hydrophobic properties of polymers can also lead to the formation of air bubbles on waste plastic aggregate surfaces. It has been discovered that controlling the morphology of the plastic aggregates may be necessary to mitigate this increase in air content. The irregular shape of recycled plastic aggregate and its immiscibility with natural sand and hydrophobic properties contribute to a notable increase in concrete's air content when utilized (Aamir Gour et al., 2020). Concrete density is reduced as plastic aggregate content increases, decreasing greater for larger and flakier plastic-aggregate particles (Vali and Asadi, 2017).

2.4.3.3 Flowability

Prior research has shown that concrete flowability is decreased by adding recycled plastic in the form of fibers (Alqahtani et al., 2017), with flowability decreasing due to a larger surface area that requires more material to provide a cover. Moreover, while fiber tended to increase the friction between concrete's parts, decreasing flowability, using plastic waste as aggregate made concrete more flowable. This decrease was brought about by the uneven angular shape of the plastic components in contrast to the rounded shape of the sand grains, increasing particle friction and decreasing the combination's workability (Sharma and Bansal, 2016). Although the rough, sharp shapes of the particles reduced concrete slump, the circular structure of the particles improved overall flowability (Babafemi et al., 2018)

2.5 Summary of Proprietary and Non-Proprietary Products Utilized in Pavement Construction Trials

Various proprietary and non-proprietary products have been utilized in pavement construction trials to enhance pavement performance, durability, and sustainability. The following section is a summary of some commonly used products in both categories:

2.5.1 Proprietary Products

2.5.1.1 Asphalt Binders

Some companies have engineered specialized asphalt binders that deliver enhanced performance attributes, including high durability, diminished rutting, and enhanced resilience against cracks. These binders present distinct compositions and qualities that surpass conventional asphalt substances. Proprietary asphalt binders are engineered to significantly enhance the long-term durability of pavements, offering robust protection against cracking, rutting, and other damage caused by heavy traffic and environmental stresses (Hall and White, 2021; Pasetto et al., 2022). These binders are formulated to maintain their intended performance over an extended period, ensuring reliable pavement integrity under diverse conditions. One of the key advantages of proprietary binders is their ability to perform across a wide range of temperatures. They are designed to resist thermal cracking at high temperatures while maintaining flexibility in colder conditions, delivering consistent and reliable pavement performance even in extreme climates. This improved temperature susceptibility is crucial for infrastructure longevity in regions with significant seasonal or daily temperature fluctuations. Superior rut resistance is another hallmark of proprietary binders. Their advanced elasticity-recovery properties allow pavements to rebound after deformation caused by repetitive traffic loads, preserving smoothness and ensuring a comfortable ride. Additionally, these binders are fortified with additives that enhance aging resistance by mitigating the effects of oxidation and solidification. This prolongs the pavement's lifespan, reducing maintenance needs and improving cost efficiency.

2.5.1.2 Asphalt Additives

Proprietary additives, such as anti-stripping agents and rejuvenators, improve asphalt-aggregate adhesion, moisture resistance, and pavement aging properties. These additives are used to modify asphalt binders, enhancing their elasticity, fatigue resistance, and temperature susceptibility (Ballester-Ramos et al., 2023). Polymer additives significantly enhance the performance of asphalt by increasing its elasticity and flexibility, enabling it to resist better deformation and fractures caused by heavy traffic and temperature fluctuations (Hall and White, 2021). This elasticity effectively allows pavements to handle substantial vehicular loads and extreme temperature variations. Additionally, polymer modification improves the asphalt's resistance to rutting, a persistent deformation resulting from repeated traffic loads. By strengthening the binder's capacity to resist flow, polymer additives help maintain the pavement's structural integrity. Incorporating polymer additives also bolsters fatigue resistance, reducing the formation and spread of interconnected cracks caused by repetitive loading cycles. This enhancement extends the pavement's operational lifespan.

Furthermore, polymer-modified asphalt performs well across a broad temperature range, remaining flexible at low temperatures to prevent thermal cracking and stable at high temperatures to resist rutting. Polymers also enhance the durability of asphalt, increasing its resistance to aging and moisture damage while improving adhesion between asphalt and aggregates for a stronger pavement structure. From an environmental perspective, some polymer additives incorporate recycled materials, which reduce waste and contribute to sustainability efforts, making polymer-modified asphalt an eco-friendly choice for modern infrastructure.

2.5.1.3 Fiber Reinforcement

Proprietary fiber reinforcement products are added to asphalt mixes to improve pavement cracking resistance and fatigue performance. They offer unique advantages over traditional reinforcement methods (Cheng et al., 2018; Skotnicki et al., 2021). Fiber reinforcement is widely utilized in pavements to enhance mechanical performance, with various types offering unique benefits. Steel fibers are known for resisting cracking and significantly improving pavement performance. Their high tensile strength makes them particularly effective in heavy-load applications. Synthetic fibers, such as polypropylene and polyester, are lightweight and corrosion-resistant and contribute to improved pavement flexibility and fatigue resistance, as demonstrated by studies conducted by Jiang et al. (2021) and Pazzini et al. (2022).

Additionally, natural fibers, like cellulose fibers derived from wood or plants, are gaining popularity for their environmental friendliness and ability to enhance the performance of asphalt and concrete pavements. Incorporating fibers into pavement materials offers several notable advantages. One of the primary benefits is increased strength, as fiber reinforcement enhances the load-bearing capacity and minimizes issues such as rutting and deformation. This improvement has been highlighted in research by (Jiang et al., 2021; Pazzini et al., 2022). Furthermore, fiber reinforcement effectively controls cracks, preventing their formation, propagation, and expansion. This property is crucial for extending pavement life and has been extensively studied, emphasizing its role in enhancing fatigue resistance and reducing the likelihood of fatigue failure (Ahmed et al., 2022; Mrema et al., 2020). These attributes collectively make fiber reinforcement an essential component in resilient pavement design (Jiang et al., 2021).

2.5.1.4 Geosynthetics

Geosynthetics, a large family of products that include geotextiles, geomembranes, geocomposites, and geomembranes, play a crucial role in modern pavement construction, providing a wide range of benefits in terms of stability, durability, and cost-effectiveness. Geosynthetics are used to reinforce pavement layers, reduce reflective cracking, and improve overall structural integrity (Mirzapour Mounes et al., 2014). Geosynthetics enhance the stability of pavement structures by distributing loads, reducing deformations, and preventing lateral movement of materials. They also provide a protective layer, mitigating the effects of stress and reducing the risk of cracks and pavement failures. Geosynthetics facilitate efficient drainage by preventing clogging and promoting the rapid removal of water from a pavement system, thereby helping maintain the integrity of the pavement and prevent moisture-related damage (Mirzapour Mounes et al., 2014; Spadoni et al., 2021). The use of geosynthetics can lead to cost savings in pavement construction. They often reduce the need for expensive aggregate materials and minimize maintenance requirements, extending pavement service life. Geosynthetics should be selected based on the specific design requirements of a particular pavement project, considering factors such as traffic loads, soil conditions, drainage needs, and environmental considerations. To ensure proper interaction and performance, proprietary geosynthetic products should be compatible with other materials used in the pavement system. To ensure long-term effectiveness, it is important to ensure that the geosynthetics selected meet the necessary quality standards and performance specifications.

2.5.1.5 Pavement Sealants

Pavement sealants, or pavement coatings or seal coats, are specialized products designed for the construction and upkeep of pavements. These proprietary solutions provide various advantages, such as shielding against water-related damage, UV radiation, oxidation, and regular deterioration. Applied onto pavement surfaces, they can safeguard against moisture penetration, oxidation, and aging, ultimately prolonging the pavement's durability and functionality (Gong et al., 2022, 2021; Skotnicki et al., 2021).

Pavement sealants play a crucial role in extending the life of pavements by providing a protective layer against environmental and traffic-related stresses. Asphalt-based sealants are the most commonly used for sealing asphalt pavements. These sealants are a mixture of asphalt binders, fillers, and additives, which form a protective coating that helps block water infiltration and prevent oxidation of the asphalt binder. Coal tar-based sealants, historically popular due to their durability and chemical resistance, have decreased use because of environmental concerns, especially related to their potential toxicity.

In contrast, acrylic-based sealants, formulated with water as a base, offer strong adhesion, flexibility, and UV resistance. They are frequently applied to concrete pavements, creating a protective shield against moisture and weathering effects. The use of pavement sealants provides several key advantages. One of the primary benefits is their protection against water damage. By sealing the surface, these sealants help reduce the risk of potholes, cracks, and general pavement deterioration caused by moisture infiltration. Sealants also offer protection against UV radiation, preventing oxidation and color fading, which helps maintain the pavement's appearance and extend its lifespan. The protective properties of sealants not only preserve the integrity of the pavement but also reduce the need for frequent repairs and maintenance. For optimal adhesion and efficacy of the sealant, it is essential to clean the pavement surface thoroughly before application. Removing dirt, debris, and loose materials ensures a strong bond between the sealant and the surface. Various application methods, such as spraying, squeegeeing, or brushing, may be employed, depending on factors like the type of sealant, the condition of the pavement, and the project scale. Maintaining the sealant’s effectiveness requires periodic reapplication, crack filling, and regular cleaning to prevent debris buildup. Properly applied and maintained sealants can significantly extend the lifespan of pavements by protecting them from environmental and traffic-induced stresses. The durability and performance of the sealant are influenced by factors such as product quality, surface preparation, application method, and prevailing traffic conditions.

2.5.2 Non-Proprietary Products

2.5.2.1 Aggregates

Non-proprietary products, specifically aggregates, are fundamental components used in pavement construction. Aggregates are granular materials such as sand, gravel, crushed stone, or sometimes recycled materials combined with binders such as asphalt or cement to create various pavement layers (Jiang et al., 2021; Pazzini et al., 2022). Aggregates play a vital role in enhancing the strength and stability of pavements by effectively distributing and transferring the weight of vehicles to the underlying layers. Aggregates' uneven shapes and angular nature create interlocking mechanisms within pavement layers that enhance overall stability and minimize the likelihood of movement or shifting. Aggregates with appropriate gradation support proper drainage throughout the pavement structure, helping prevent water accumulation and reducing the risk of pavement deterioration due to moisture-related issues. Aggregates significantly influence the surface texture of pavements. They provide sufficient skid resistance, ensuring vehicle traction and enhancing road safety. Aggregate quality is crucial for pavement performance. Specifications often include requirements for gradation, particle shape, abrasion resistance, durability, and specific mechanical properties. Local or regional transportation agencies typically establish aggregate specifications and guidelines based on performance requirements and local material availability. Aggregate quality can profoundly impact pavement performance. Specifications often include gradation, particle shape, abrasion resistance, durability, and specific mechanical attributes. These specifications are typically established by local or regional transportation agencies and tailored to meet performance demands and local material availability. Aggregates undergo rigorous testing to ascertain their conformity with specifications and suitability for pavement construction. Tests typically include sieve analysis, specific gravity measurement, aggregate crushing value assessment, abrasion resistance determination, and soundness tests. Quality control measures are imperative to ensure that aggregates meet necessary standards and performance benchmarks in pavement construction. This involves maintaining consistent sampling, testing, and inspection protocols to uphold the required standards and criteria.

2.5.2.2 Portland Cement

Portland cement is a non-proprietary product widely used in pavement construction as a binding material in concrete and cement-based pavement layers. Hydraulic cement forms a strong and durable matrix when mixed with aggregates and water(Más-López et al., 2020; Rasheed et al., 2022). Portland cement is primarily composed of calcium silicates, aluminates, and ferrites. The production of Portland cement involves using raw materials like limestone, clay, shale, iron ore, and other minerals. The manufacturing process entails extracting and grinding these raw materials, followed by high-temperature kiln firing, with the resulting clinker finely ground to create Portland cement. In concrete and cement-based pavement layers, Portland cement functions as a binding agent, uniting aggregates to form a cohesive and solid structure. When combined with water, it undergoes hydration, a chemical reaction that generates hydrated calcium silicate compounds, gradually strengthening and hardening pavement layers over time. Concrete pavements reinforced with Portland cement possess remarkable load-bearing capability, rendering them suitable for heavy traffic and high-stress scenarios. These pavements also exhibit resilience against wear, weathering, and chemical impacts, contributing to their enduring durability. Portland cement adheres to multiple standards and specifications, often set by ASTM International and national/regional transportation agencies. Quality control protocols are implemented to guarantee that Portland cement aligns with defined physical and chemical criteria, covering aspects like fineness, setting time, strength progression, and chemical makeup. Since the production of Portland cement entails substantial energy consumption and results in the release of greenhouse gases, the industry is actively working to mitigate carbon emissions and enhance sustainability. This involves adopting alternative fuels, raw materials, and the innovation of low-carbon cement varieties. Types of Portland cement include:

- Type I: General-purpose Portland cement suitable for most pavement applications.
- Type II: Portland cement with moderate sulfate resistance, often used in areas with potential exposure to sulfate-rich soils or water.
- Type III: High-early-strength Portland cement that rapidly develops strength, suitable for situations requiring quick construction turnaround.

- Type IV: Low-heat Portland cement used in large concrete structures to minimize the heat generated during hydration.
- Type V: High-sulfate-resistant Portland cement in pavements exposed to severe sulfate conditions.

2.5.2.3 Fly Ash and Slag

Non-proprietary products, such as fly ash and slag, are commonly used as supplementary cementitious materials in pavement construction (Yoshitake et al., 2015). Fly ash is a byproduct generated from coal combustion in power plants. This fine powder is comprised of spherical particles and is used in pavement construction due to its beneficial properties. Fly ash is commonly employed as a partial substitute for Portland cement in concrete mixtures; its inclusion enhances workability, diminishes heat generation, boosts long-term strength, and reduces the likelihood of cracking. The incorporation of fly ash contributes to the endurance of concrete pavements by decreasing permeability and increasing resistance against chemicals, abrasion, and the effects of freeze-thaw cycles. The utilization of fly ash in pavement construction helps lessen the reliance on Portland cement, thus conserving natural resources and mitigating the carbon emissions associated with cement production. Furthermore, fly ash is often more cost-effective than Portland cement, leading to potential cost savings in pavement projects.

Slag is a byproduct from the iron and steel sector formed during the smelting process of iron ore. This substance is comprised of a combination of silicates and oxides. In pavement construction, the most prevalent variant of slag utilized is ground granulated blast-furnace slag (GGBFS). GGBFS serves as a partial substitute for Portland cement in concrete mixes, where its inclusion significantly bolsters the concrete pavement strength and longevity. It contributes to heightened compressive strength, reduced permeability, and enhanced resistance against sulfate attacks and alkali-silica reactions. Slag also has a lower heat of hydration than Portland cement, mitigating the risk of thermal cracking in concrete pavements. Integrating slag into pavement construction has dual sustainability benefits; it curbs waste generation within the steel industry while concurrently diminishing the carbon footprint associated with cement production.

Fly ash and slag both demand appropriate storage and handling practices to avert moisture infiltration that could compromise their effectiveness. These materials are typically introduced into concrete mixes during the batching stage. It's imperative to adhere to recommended guidelines and specifications for proportions and blending methods. Fly ash and slag used in pavement construction must conform to defined quality standards often established by ASTM International or local transportation agencies. Quality control measures should be implemented to ascertain that fly ash or slag meets the requisite chemical and physical attributes for use in pavement construction.

2.5.2.4 Emulsified Asphalt

Emulsified asphalt is a non-proprietary product comprised of asphalt cement, water, and an emulsifying agent. Emulsified asphalt offers several advantages in terms of ease of application, versatility, and cost-effectiveness (Li et al., 2019; Skotnicki et al., 2021; Wang et al., 2020). The two main types of emulsified asphalt are Anionic Emulsified Asphalt (has negatively charged asphalt particles and is commonly used for surface treatments, such as chip seals and slurry seals.) and Cationic Emulsified Asphalt (has positively charged asphalt particles and is typically used for a wide range of applications, including tack coats, micro surfacing, and fog seals.). Emulsified asphalt significantly enhances adhesion and bonding between pavement layers, thereby augmenting a pavement's structural strength and overall integrity. It establishes a protective barrier on the pavement's surface, effectively barring water infiltration and shielding underlying layers from moisture-induced harm. A frequent application for emulsified asphalt is in surface treatments like chip seals and slurry seals that effectively seal cracks, reinstate surface texture, and furnish a surface with improved skid resistance (Li et al., 2019; Skotnicki et al., 2021; Wang et al., 2020). Emulsified asphalt is pivotal in pavement preservation strategies, contributing to the lifespan extension of existing pavements. Sealing and protecting pavements against aging, oxidation, and wear is integral to sustaining pavement longevity. Emulsified asphalt is commonly applied to utilize specialized equipment like distributor trucks or spreaders to ensure even distribution across the pavement surface. Before applying emulsified asphalt, meticulous surface preparation is vital, encompassing tasks such as cleaning and addressing any existing cracks or damage. The application of emulsified asphalt serves varied purposes, including prime coating, tack coating, surface treatment, and participation in pavement preservation techniques. The choice of application depends on the needs and goals of the specific project.

2.5.2.5 Reclaimed Asphalt Pavement (RAP)

Reclaimed Asphalt Pavement (RAP) is a non-proprietary product comprised of recycled asphalt pavement that has been removed from existing roads or parking lots and processed for reuse (Rout et al., 2023). RAP is generated by milling or full-depth removal of existing asphalt pavements, typically during rehabilitation or reconstruction projects. After removal, the asphalt pavement is processed through crushing and screening to produce RAP, which is comprised of aggregates coated with aged asphalt binder. RAP contributes to sustainable practices by lessening reliance on virgin materials and conserving natural resources. It is generally more cost-effective than virgin materials, resulting in financial benefits for pavement projects. Introducing RAP into asphalt mixes can enhance pavement performance, elevating rut resistance, fatigue life, and overall durability. Moreover, incorporating RAP diminishes the necessity for new aggregate and asphalt production, reducing energy consumption and greenhouse gas emissions.

RAP finds application in diverse asphalt mixture types, including hot-mix asphalt (HMA), warm-mix asphalt (WMA), and cold-mix asphalt (CMA). The proportion of RAP in the mix design varies, contingent upon local specifications, pavement conditions, and performance requisites. Adequate processing and mixing techniques are indispensable for achieving uniform dispersion of RAP within the asphalt mixture and attaining the desired performance attributes. Local transportation agencies and industry norms typically define specifications for RAP utilization in pavement construction. Quality control measures encompass parameters like gradation, asphalt content, and RAP cleanliness to ensure compliance with required specifications and performance standards. Proprietary recycled plastic producer information is presented in Table 2.13, and other potential recycled plastic producers' information is presented in Table 2.14.

Table 2.13 The Proprietary Recycled Plastic Producers

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
1	Macrebur (Southern California)	U.S.	Website: https://www.macrebur.com/ E-Mail: info@macrebur.com Tel.: 6199942501	Pelletized industrial and post-consumer plastic bottles and bags	MR6 & MR8	MR6 and MR8 are both manufactured from a mix of polymers	MR6 is used where traditionally polymer-modified bitumen's (PMBs) are specified. This might be on motorways, heavy-duty base courses or where surface courses are subject to heavily loaded traffic. MR6 provides a direct replacement to virgin polymer, used in producing PMB. MR8 is used where unmodified binder (liquid asphalt) is normally specified, for instance, all base, binder, and surface course asphalt material on standard traffic roads, footways, etc. MR8 is used as a direct replacement for neat binder used in asphalt and is typically dry mixed at asphalt plant.	
2	Elvaloy by Dow	U.S.	Website: https://www.dow.com/en-us Multiple branches in U.S. https://corporate.dow.com/en-us/locations.html	An asphalt binder additive produced from waste shopping bags	Recycled polymer modified asphalt (RPMA)	Post-consumer recycles content (PCR) (The base asphalt binder is modified by adding the PCR with ELVALOY™ RET to the asphalt.)	Sustainable roads with excellent performance, long service life, and lower life-cycle costs compared to conventional, neat asphalt.	ELVALOY™ 5170 / ELVALOY™ 4170 Copolymer: A Reactive Terpolymer (RET) that can be used to modify the properties of asphalt used in paving. It has been specially designed to give the best performance and value while minimizing safety hazards on the road.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
3	NeoPave (formerly G5) by Technisoil Industrial	U.S.	E-Mail: info@technisoilind.com	A urethane polyol-based binder with waste plastic bottles	-	Recycling 100% of the existing road in place, and approximately 150,000 plastic bottles per lane mile.	Roads recycled with Neo possess the strength of concrete and the flexibility of asphalt. Neo enhanced pavement lasts 2 – 3 times longer than asphalt, has 5X the tensile strength of asphalt with greater flexibility. Neo also helps eliminate rutting and provides extremely high reflective cracking resistance while delivering at least 50% life-cycle savings to taxpayers.	https://neopave.com/ Neo is used to modify a common process called cold in-place recycling. We mill up failing asphalt, crush and resize it, mix it with Neo, and immediately repave it. We eliminate the need to haul 84 trucks of asphalt out/in, and return to traffic within hours, instead of days or even weeks.
4	Altisora	U.S.	Website: https://www.osti.gov/biblio/1756319 E-Mail: info@altisora.com	Salvaged ocean fishing net fiber additive to modify asphalt	AltiFiberPLUS	Creating an asphalt additive based on ocean plastic, namely ocean bound fishing nets	AltiFiberPLUS, is a formulation from discarded fishing nets that improves road strength and durability. AltiFiberPLUS has shown to improve rutting and cracking of commercial asphalt mixes by 44% and 16% respectively. Planning to introduce the next ocean plastic asphalt additives in the family: AltiBinder and AltiFiber	
5	New Village Initiative Advanced Materials Group (NVI)	U.S.	Website: https://www.nviamg.com/products E-Mail: info@nviamg.com Tel.: (800)583-3892	Asphalt binder additives and concrete aggregate replacements blended from recycled plastic polymers		Recycled Hybrid-Polymer/Plastic-Based additives	Concrete: Lightweight concrete: faster, cheaper, more per truckload Asphalt Decrease Hamburg rutting by up to 50% Increase pavement life by up to 50%	
6	Huesker International	Germany	E-Mail: marketing@HUESKER.com Tel.: 800 942 9418	Asphalt reinforcement grid as well as geogrids for subgrade soil and aggregate base reinforcements	Fortrac and HaTelit geogrids (various types)	Made from 100 % recycled PET bottles	Fortrac Geogrid for soil reinforcement: Highly resilient, flexible geogrid with a proven track record in soil reinforcement. HaTelit Asphalt Reinforcement Geogrid: allows a significant extension of renovation intervals. Thus, the useful life of the traffic areas is extended. Because of the associated reduction in maintenance costs, HaTelit offers a very economical solution for the repair of road surfaces.	Fortrac: https://www.huesker.us/geosynthetics/products/grids/fortrac/ HaTelit: https://www.huesker.us/geosynthetics/products/grids/hatelit/

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
7	FORTA	U.S.	Website: https://forta-ferro.com/ Email: info@fortacorp.com Tel: 724-458-5221	fiber for concrete reinforcement	Fiber	Various Materials	Concrete reinforcement	Some Products FORTA-FERRO FERRO-GREEN (Made of recycled polypropylene and copolymer macro fibers)
8	NecoTECH	U.S.	Website: https://necotech.com/ Address: Delaware Entrepreneurial Center Ohio Wesleyan University 70 S Sandusky St, Suite 210 Delaware, OH 43015 Tel: 833-444-NECO (6326)	Sustainable Materials	Asphalt Concrete Plastic Building materials	Waste Materials	Infrastructure and building materials Pavement	Some Products NecoPlastics NecoWaste NecoCrete NecoPave

Table 2.14 Other Potential Recycled Plastics Facilities

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
1	Mid America Recycling (MAR)	U.S.	2742 East Market Street, Des Moines, IA 50317 515-265-1208/ info@midamericarecycling.com http://www.midamericarecycling.com/	Paper Metal Plastics	Recycled Plastics PDE, HDPE	Various types of Waste Plastics	Comprehensive, multi-material usage	Largest recycling facility in Iowa and offers both residential and commercial single stream processing capabilities. Four grades of plastics, including large volumes of PETE, LDPE, HDPE and PVC are sorted, cleaned and processed into large bales for shipment to both domestic and international recyclers. In addition to the single stream recycling facility in Des Moines, MAR offers the following services in the locations: Sioux City, IA - Granulate plastic/Cedar Rapids, IA - Baling aluminum, plastic, granulate plastic/Sioux Falls, SD - Baling aluminum and plastic.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
2	Cedar Rapids/Linn County Solid Waste Agency	U.S.	https://www.solidwasteagency.org/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	An intergovernmental agency operating two facilities in Linn County. Most plastic material types except PS are accepted for recycling.
3	Clinton County Area Solid Waste Agency	U.S.	4292 220th St., Clinton, IA 52732 563-243-4749/ ccaswa@ccaswa.com http://ccaswa.com/home/4089824	Landfill solid waste management services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	An intergovernmental agency serving the County of Clinton for solid waste disposal and recycling programs. Plastic food containers from most plastic material types are accepted for recycling.
4	Metro Waste Authority	U.S.	300 East Locust Street, Suite 100, Des Moines, IA 50309 515-333-4430/ jme@mwatoday.com (to Judi Mendenhall, Director of Recycling & Diversion) https://www.mwatoday.com/	Versatile Recycling Services	Recycled Plastics HDPE, LDPE	Various types of Waste Plastics	Comprehensive, multi-material usage	An independent government agency to manage the landfill for the Polk County area Has a plan to building its own MRF.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
5	Cedar Poly, LLC	U.S.	200 Commerce Blvd, Tipton, IA 52772 563-886-2811 http://cedarpoly.com/	Versatile Recycling Services	Recycled Plastics HDPE, LDPE	Various types of Waste Plastics	Comprehensive, multi-material usage	An Iowa based the recycling and plastics-processing company Has processing capabilities for plastics, including grinding, washing and pelletizing HDPE, LDPE and PPS.
6	Envirovision Technologies, LLC	U.S.	1959 South 21st Street, Clinton, IA 52732 855-333-0133/ info@evtusa.com http://evtusa.com/index.html	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	The Iowa office of Envirovision Technologies, LLC. Provide injection grade regrind and reprocessed materials including HDPE, PP, PETE, and LDPE.
7	MDK ZeroLandfill	U.S.	625 Klenske Avenue, New Hampton, IA 50659 641-394-2129 https://mdkzerolandfill.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	A supplier for recycled plastics, metals, textiles and paper.
8	Quincy Recycle	U.S.	6281 N. Gateway Dr., Marion, IA 52302 319-382-2132 ccrawford@quincyrecycle.com (to Chad Crawford, General Manager of IA plant) https://www.quincyrecycle.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	Has plastic recycling processing capabilities of most of plastic type.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
9	Plastic Recycling of Iowa Falls, Inc.	U.S.	10252 Hwy. 65, Iowa Falls, IA 50126 Ph. 641-648-5073/ info@plasticrecycling.us http://plasticrecycling.us/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	A manufacturing company for recreational/traffic control/lumber products from recycled plastic.
10	Renewablade	U.S.	1200 Prairie Dr. Bondurant, IA 50035 515-778-4504 Bian Meng, 515-809-9717, brianm@renewablade.com Nick Wylie, Partner, 515-577-2011, nick@jpettiecord.com http://www.renewablade.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	The survey was not distributed due to its business. A company processing wind turbine blades into glass fibers and composite fillers
11	Chesapeake Materials Services	U.S.	https://cmsplastic.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	-

2.6 Review of Potential Impact on Environment and Occupational Health and Safety

Plastic products often incorporate additives such as plasticizers, flame retardants, photo stabilizers, antioxidants, and pigments, and many of these additives are known to be hazardous or have the potential for being carcinogenic, mutagenic, or disruptive to the endocrine system of aquatic organisms (Awange and Kyalo Kiema, 2022). Moreover, plasticizers, even at low levels (ng/L and µg/L) as phthalate esters, are considered endocrine disruptors (Botcherby, 2020). Additives may also contain metals such as Al, Cr, Ni, Zn, and Sn (Al: Aluminum (or Aluminium in British English), Cr: Chromium, Ni: Nickel, Zn: Zinc, and Sn: Tin) that may leach at concentrations dangerous to human health (Gunaalan et al., 2020). Because plastic additives are not chemically bonded to the polymer matrix, they have the potential to migrate into the surrounding environment (Awange and Kyalo Kiema, 2022), and chemicals may also leach out due to plastic deterioration (Reddy et al., 2022) (Canopoli et al., 2020).

Antioxidants such as bisphenol have high solubility in water and may affect the human reproductive system (Botcherby, 2020). In addition, Bisphenols can also impact reproduction in aquatic organisms (Liu et al., 2021). Dyes, pigments, UV filters, and photoinitiators might also migrate into the environment (Botcherby, 2020).

Plastic's most commonly reported toxic elements are ethylene dichloride, dioxins, phthalates, lead, and cadmium (Reddy et al., 2022). Phthalates, commonly present in bottles and disposable plastics, typically exhibit stability under neutral pH conditions, but they begin to leach when exposed to acidic pH and elevated temperatures. These phthalates contain significant levels of toxic substances believed to possess a high carcinogenic potential (Reddy et al., 2022).

The available literature offers few studies on the mechanisms of phthalate liberation in soil. Such plastic leaching studies are critical for civil and environmental applications involving more beneficial use of recycled plastic. Plastic leaching research is critical for use in infrastructure and geo-environmental applications.

The leaching characteristics of plastics depend on their type and chemical composition. Metal leaching from various plastic wastes, such as plastic in municipal solid waste, reclaimed plastic, bottles, and PVC gloves, has been mentioned in a few studies (Reddy et al., 2022). Metal concentrations have been below drinking water limits, except for lead and cadmium from single-use plastics used in unbound materials (Reddy et al., 2022).

In addition to the potential leaching of the additives into the environment, another problem may be the degradation of plastics into microplastics due to exposure to environmental conditions that may change their physical and chemical properties. Results related to the toxicity characteristic leaching procedure (TCLP) of several plastic types, such as PET, HDPE, PVC, LDPE, PP, PS, and Polycarbonate (PC), have shown that PET was the plastic with the lowest number of microplastic particles (Mortula et al., 2021). For example, microplastics from PET contained 4,099 items/L compared to 19,868 items/L from PC and 138 items/L from a blank solution (Mortula et al., 2021). Sand samples collected from beaches in Guadalupe were found to contain microplastics (Catrouillet et al., 2021) composed of polyethylene, polypropylene, and polystyrene, respectively 54%, 37%, 5% by weight, of the total microplastic mix (Catrouillet et al., 2021). In performing leaching tests and acidic digestion on sand samples, Al, Zn, Ba, Cu, Pb, Cd, Mn, and Cr (Al: Aluminum, Zn: Zinc, Ba: Barium, Cu: Copper, Pb: Lead, Cd: Cadmium, Mn: Manganese, and Cr: Chromium) were present as additives and pigments in these microplastics. It was felt that only Cadmium (Cd) could represent a danger when ingested by fish (Catrouillet et al., 2021).

Additives can also release microbial growth, forming biofilms (bacterial colonies) on microplastic surfaces exposed for an extended time to environmental conditions. Biofilms can either slow down or increase the leaching process of additives from microplastics by acting as a barrier for chemicals, but they also may comprise a reactive barrier and increase the polarity of additives (Awange and Kyalo Kiema, 2022). For example, microorganisms may have the ability to hydroxylate Pulmonary arterial hypertension (PAH) from naphthalene to benzo[a]pyrene (Cerniglia, 1984). Microplastic additives can facilitate the growth of microorganisms by acting as a source of nutrients, thus promoting microbial proliferation (Awange and Kyalo Kiema, 2022).

In civil infrastructures, recycled plastic can be incorporated into other materials. For example, HDPE, LDPE, PP, and PET have been incorporated with other components, such as recycled crushed concrete aggregates and asphalt binders used in flexible pavements (Shopnil, 2022). However, using plastic in road pavements raises concerns about the potential risk of microplastic released into the environment. While the use of HDPE, LDPE, PP, and PET has been tested and found not to pose any threat to the ecological system when used in base and surface layers in road pavements, even under adverse conditions of repetitive loading cycles (Shopnil, 2022), the use of PVC in asphalt binder at temperatures higher than 50°C may release traces of dioxins (Reddy et al., 2022). However, additional research is needed in this area. Conversely, studies on using recycled plastic in unbound layers, such as subgrade, subbase, and base layers, have found it effective in enhancing the mechanical properties of the materials without affecting the leaching characteristics (Reddy et al., 2022).

Recycled plastic incorporation into transportation infrastructure systems faces particular challenges, with recycling plastic at a recycling center, sorting the waste, and categorizing it into its different types, which are the most critical (Wu and Montalvo, 2021). Another challenge is the achievement of compatibility between recycled plastic and the transportation infrastructure system, let alone the various types of plastic waste (Wu and Montalvo, 2021). In polymer chemistry, compatibilization refers to incorporating a substance into an immiscible mixture of polymers to enhance the stability of the combined system (Pyle, 2020). Transportation infrastructure systems comprised of soil, asphalt, and concrete are complex molecules of organic molecules in which undesirable mechanical qualities may result from a lack of compatibility or balance, as seen in component phase separation (Pyle, 2020). While the literature suggests several techniques to increase compatibilization, more research is required on these cutting-edge techniques' feasibility and adaptation to the various requirements of transportation infrastructure systems in terms of engineering properties and workability.

The danger of worker exposure to potentially toxic substances in plastics is a significant safety concern related to the use of recycled plastics (Masuduzzaman et al., 2018) (Wu and Montalvo, 2021); hazardous compounds such as acrolein, formic acid, and ethylbenzene could be released when heating plastics such as PP, PE, and PS (Makri et al., 2019). The use of recycled plastics in transportation infrastructure systems raises an additional issue: the possibility of plastics degrading into microplastics and entering the local ecology and bodies of water. Moreover, recycled plastics' mechanical properties may degrade more than virgin polymers made from the same resource as waste plastics.

2.7 Plastic Degradation

Changes in plastic properties (e.g., mechanical, optical, thermal characteristics) can result from polymer degradation that can occur in various ways and from numerous factors. The underlying reasons for plastic degradation can usually be attributed to (Alassali et al., 2021):

- (i) plastic composition, especially when the migration of additives produces irreversible tacking and warping phenomena;
- (ii) aging, which results in chemical instability over time;
- (iii) environmental factors such as light, high-energy radiation (UV, gamma radiation), microorganisms (i.e., bacteria or fungi), temperature, and humidity; and
- (iv) improper usage and cleaning of objects (see Table 2.15)

Polymer degradation can be categorized into abiotic and biotic degradation. Abiotic degradation involves chemical or physical changes, while biotic degradation refers to biodegradation, and chemical and physical degradation rates are generally higher than biodegradation rates. Degradation can occur either within a bulk material or on its surface. In bulk degradation, chain scission and thermodynamic changes in state occur, possibly leading to a decrease in molecular weight and mechanical strength. Surface erosion, on the other hand, results in the loss of material only on the surface, without significant changes in molecular weight or mechanical strength. Surface degradation occurs when the polymer interacts with the external environment, forming fine cracks and morphological transformations. Observable changes in properties may suddenly occur after a certain degradation time, and degradation of plastics can also cause chemical changes, resulting in the formation of new functional groups and polymer contamination, with such contaminants potentially affecting reprocessing and the quality of the product. Chemical degradation mechanisms such as oxidation and hydrolysis can alter polymer properties under environmental aging conditions. Melt degradation, long-term heat aging, and weathering are classified as relevant processes based on the life-cycle periods of polymers.

Table 2.15 Types of polymer degradation and the chief factors inducing degradation Source of Data: (Alassali et al., 2021)

Type of Degradation or Decomposition	Degrading Agent
Photochemical degradation	Light (UV, visible light)
High energy radiation-induced degradation	X-rays, gamma rays, fast electrons
Photo-thermal or photochemical, ablative photo-degradation	Laser
Electrical ageing	Electrical field
Corrosive degradation, etching	Plasma
Biological degradation	Microorganisms
Mechanical degradation	Stress forces

Type of Degradation or Decomposition	Degrading Agent
Physical degradation, environmental stress, cracking	Abrasive forces
Ultrasonic degradation	Ultrasound
Chemical degradation or decomposition, etching, solvolysis, hydrolysis	Chemicals (acids, alkalis, salts, reactive gases, solvents, water)
Thermal degradation or decomposition	Heat
Oxidation, oxidative degradation and/or decomposition, ozonolysis	Oxygen, ozone
Thermo-oxidative degradation and/or decomposition, combustion	Heat and oxygen
Photo-oxidation	Light and oxygen

2.8 Management of Plastic Wastes

Plastic waste disposal can be associated with various health risks, including respiratory disorders, ingestion of toxic chemicals, and poisoning of animals that humans consume for food. Plastics produced in many consumable products contain toxic chemicals like phthalates, heavy metals, and bisphenol A, all of which can adversely affect humans. For example, exposure to bisphenol A has been linked to developmental and reproductive problems, while phthalates have been associated with hormonal imbalances and cancer (Jung et al., 2022; Prajapati et al., 2021).

Plastics constitute approximately 10% of household waste, most of which ends up in landfills, following the common practice of landfilling in many countries. However, the scarcity of landfill space has become a significant problem. In the past, landfilling was favored in the UK for its cost-effectiveness and simplicity, but it is currently the least preferred waste management option for plastic waste (Prajapati et al., 2021). Landfills raise concerns about environmental and public health due to the presence of toxic chemicals that can potentially leach into the surrounding areas. Proper management of landfills can help reduce environmental pollution and health risks, but there is always a possibility of soil and groundwater contamination from decomposed plastic byproducts and additives that persist in the environment over the long term (Geyer et al., 2017).

Incineration of plastic waste is an alternative to landfilling, but concerns have arisen about releasing hazardous chemicals into the atmosphere during such a process. When plastic waste is incinerated, fumes containing halogenated additives, polyvinyl chloride, furans, dioxins, and polychlorinated biphenyls (PCBs) are emitted, all posing environmental risks (Geyer et al., 2017; Tejaswini et al., 2022). Combustion of plastics leads to air pollution by releasing noxious fumes into the atmosphere. Moreover, incineration of plastics can damage the combustion heaters of flue systems, and the byproducts of plastic combustion tend to be harmful to humans and the environment (Prajapati et al., 2021). Certain low molecular weight compounds can vaporize directly into the air, contributing to air pollution. Depending on their properties, some compounds may form a combustible mixture, while others may oxidize in solid form. While plastic incineration as a method of waste management is less commonly used due to its potential pollution impact on the environment, countries such as Sweden, Denmark, and Japan have constructed massive incinerator facilities for managing municipal solid waste, including plastics (Jung et al., 2022; Prajapati et al., 2021). Plastic incineration has the advantage of recovering energy from plastic waste. Hungary has enacted regulations that allow only licensed plastic waste incineration plants to incinerate plastics, while all other forms of burning plastic waste are banned. Table 2.16 lists the compounds generated and their harmful effects during the incineration of polyvinyl chloride.

Table 2.16 Compounds generated during the incineration of polyvinylchloride and their harmful effects Source of Data: (Gilpin et al., 2005; Okunola A et al., 2019)

Compound	Health effect(s)
Acetaldehyde	Damages the nervous system, causing lesions.
Acetone	Irritates the eyes and the respiratory tract.
Benzaldehyde	Irritates the eyes, skin, and respiratory system and limits brain function.
Benzole	Carcinogenic adversely affects the bone marrow, the liver, and the immune system.
Formaldehyde	Serious eye damage, carcinogenic, may cause pulmonary edema.
Phosgene	Gas used in the WWI. Corrosive to the eyes, skin, and respiratory organs.
Polychlorinated dibenzo-dioxin	Carcinogenic irritates the skin, eyes, and respiratory system. It damages the circulatory, digestive, and nervous systems, liver, and bone marrow.
Polychlorinated dibenzofuran	Irritates the eyes and the respiratory system, and causes asthma.
Hydrochloric acid	Corrosive to the eyes, the skin, and the respiratory tract.
Salicyl-aldehyde	Irritates the eyes, the skin and the respiratory tract. It can also affect the central nervous system.
Toluene	Irritating the eyes and the respiratory tract can cause depression.
Xylene	Irritates the eyes. It can also affect the central nervous system, reducing consciousness and impair learning ability.
Propylene	Damages the central nervous system by lowering of consciousness.
Vinyl chloride	Carcinogenic, irritating to eyes, skin, and respiratory system. Effect on the central nervous system, liver, spleen, blood-forming organs.

Plastic recycling is a major aspect of worldwide efforts to minimize the yearly 8 million tons of plastics in the waste stream entering the Earth's oceans. Recycling of plastics involves reprocessing recovered plastic scraps or wastes into usable products. However, one of the main challenges associated with plastic recycling is the lack of proper waste management infrastructure in many countries, which makes it challenging to collect, sort, and recycle plastic waste (Cássio et al., 2022; Landrigan et al., 2020; Tansel, 2022). Another challenge is the lack of consumer awareness and participation in recycling programs, resulting in low recycling rates (Geyer et al., 2017). Some plastics are difficult to recycle due to their chemical composition, making them unsuitable for certain recycling processes. Additionally, the issue of plastic contamination that occurs when non-recyclable materials are mixed with recyclable plastics makes it challenging to recycle contaminated plastics (Hahladakis et al., 2018; Stoiber et al., 2020). The economics of plastic recycling can be challenging; recycling may be higher than the cost of producing new plastic.

2.9 Potential Impact of Plastic on the Environment

2.9.1 Land Pollution

While plastic waste and products can damage and contaminate the terrestrial environment, and the problems may subsequently be transferred into the aquatic environment, there is a shortage of data related to the volume of plastic waste on land compared to the voluminous data that exist on plastic debris in marine habitats (Alassali et al., 2021). Dumping or landfilling plastics on land leads to abiotic and biotic degradation of plastics, and the environmental effects can persist long-term. Effective management and recycling of plastic waste are required to reduce land pollution.

2.9.2 Water Pollution

Plastic waste and products can contaminate the aquatic environment and cause significant harm to marine organisms. About 80% of plastic waste present at sea originates from land-related sources. Plastic waste can break down into microplastics that can be ingested by marine organisms and enter the food chain (Hahladakis et al., 2018). Effective management and recycling of plastic waste are also required to reduce water pollution, and there is an urgent need for a ban on plastic waste disposal into the sea to prevent further pollution.

2.9.3 Air Pollution

Open burning of plastic waste and plastic products releases pollutants such as heavy metals, dioxins, PCBs, and furans, all of which can represent health risks, especially respiratory disorders (Cássio et al., 2022). The role of plastics in affecting air pollution in developing and poor countries is much more pronounced, potentially having a massive impact on future generations. Therefore, regulations are needed to prevent the open burning of plastic waste and products and to manage plastic waste.

2.9.4 Effects of Plastic Wastes on Animals

Plastic waste can harm animals through ingestion and entanglement, with ingestion being more frequent than entanglement. The ingestion of plastic waste can cause physical harm, such as blockages in the digestive system, and can also lead to the accumulation of toxic chemicals in an animal's body (Cássio et al., 2022). Plastic waste can also entangle animals, leading to injury, suffocation, and death. Marine animals are particularly vulnerable to plastic waste, with large amounts of plastic waste entering the world's oceans and threatening the survival of marine animals (Tansel, 2022). There is a need for effective management and recycling of plastic waste to reduce harm to animals and their habitats.

2.9.5 Public Health Effects of Plastic Wastes

Plastic polymers are generally considered to be of little concern to public health, but some additives and residual monomers can pose health risks (Gilpin et al., 2005). Most additives in plastics are potential carcinogens and endocrine disruptors, and humans may be exposed to these additives through ingestion, skin contact, and inhalation. Skin contact with some of the plastic additives can also cause dermatitis (Cássio et al., 2022). Table 2.17 summarizes the various additives used in plastic production, their public health effects, and the types of plastics involved.

Table 2.17 Various additives used in plastic production and their health effects and the plastic types Source of Data: (Gilpin et al., 2005; Okunola A et al., 2019)

Toxic Additives	Applications	Public health effect(S)	Plastic types
Bisphenol A	Plasticizers, can liner	Mimics estrogen, Ovarian disorder	Polyvinyl chloride (PVC), Polycarbonate (PC)

Toxic Additives	Applications	Public health effect(S)	Plastic types
Phthalates	Plasticizers, artificial fragrances	Interference with testosterone, sperm motility	Polystyrene (PS), Polyvinyl chloride (PVC).
Persistent Organic Pollutants (POPs)	Pesticides, flame retardants, etc.	Possible neurological and reproductive damage	All plastics
Dioxins	Formed during low-temperature combustion of PVC	Carcinogen interferes with testosterone	All plastics
Polycyclic aromatic hydrocarbons (PAHs)	Use in making pesticides	Developmental and reproductive toxicity	All plastics
Polychlorinated biphenyls (PCBs)	Dielectrics in electrical equipment	Interferes with thyroid hormone	All plastics
Styrene monomer	Breakdown product	Carcinogens can form DNA adducts	Polystyrene
Nonylphenol	Anti-static, anti-fog, surfactant (in detergents)	Mimics oestrogen	PVC

2.9.6 Environmental and Health Impacts of Microplastics

Microplastics have become a pervasive environmental pollutant, and their worldwide presence in various ecosystems has been documented. The accumulation and persistence of microplastics can have significant environmental and health impacts. Microplastics threaten marine ecosystems, terrestrial environments, and human health. In marine ecosystems, they are often ingested by organisms, causing physical harm and digestive blockages while also accumulating in tissues and magnifying the food chain, disrupting entire ecosystems (Landrigan et al., 2020; Momeniha et al., 2017; Tansel, 2022). Sensitive habitats, such as coral reefs, are particularly vulnerable, with microplastic contamination reducing biodiversity and degrading ecosystems. On land, microplastics infiltrate soils, disrupting microbial communities and potentially contaminating agricultural lands. They also pollute freshwater systems via runoff, adversely affecting aquatic organisms and potentially contaminating drinking water sources. Microplastics present multiple exposure pathways for humans, including ingestion through food and water, inhalation of airborne particles, and potential toxic effects from pollutants adsorbed onto their surfaces. These particles can enter the human body, raising concerns about long-term health effects such as impacts on immune function, hormonal balance, and disease development. While the full extent of health risks is not yet fully understood, the presence of microplastics in the environment underscores the urgent need for research and intervention to mitigate their adverse effects. It is important to note that while there is growing evidence of environmental and health impacts associated with microplastics, more research is needed to fully understand the extent of these effects, their mechanisms, and their potential long-term consequences. Efforts are underway to address microplastic pollution through regulations, mitigation strategies, and public awareness campaigns to minimize environmental and health risks.

2.9.7 Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) in Plastic Waste

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are a class of synthetic chemicals widely used in various industries and consumer products due to their unique properties, including resistance to heat, water, and grease. While PFAS are commonly found in plastic materials because they enhance the performance and durability of plastics, the presence of PFAS in plastic waste poses unique environmental and health concerns. PFAS (per and poly-fluoroalkyl substances) are intentionally incorporated into plastic products during manufacturing to impart properties like water resistance and non-stick characteristics (Anderko and Pennea, 2020; Tansel, 2022). This results in plastic waste containing PFAS from various sources, including consumer goods and industrial processes. Their persistence in the environment makes PFAS particularly concerning, as they remain intact for long periods and contaminate soil, water, and air. When leached from plastic waste, PFAS poses risks to ecosystems, with the potential for bioaccumulation and biomagnification, leading to higher concentrations in organisms up the food chain. Health risks associated with PFAS exposure are significant, involving ingestion, inhalation, and dermal contact pathways. Linked to liver damage, developmental issues, immune dysfunction, and certain cancers, PFAS presents growing public health concerns, though more research is needed to understand the impacts of long-term, low-level exposure. Regulatory actions are increasing globally, including restrictions on specific PFAS compounds in plastic products. However, managing PFAS in plastic waste remains challenging, as their presence complicates recycling efforts and can perpetuate contamination in recycled materials, necessitating innovative solutions to mitigate their environmental and health impacts. Addressing the issue of PFAS in plastic waste requires a combination of measures, including regulations, improved waste management practices, use of alternative, non-toxic materials, and continued research to understand the risks better and develop effective mitigation strategies (Hahladakis et al., 2018). Minimizing the use of PFAS in plastic manufacturing and promoting sustainable and circular approaches to plastic waste management are essential for reducing PFAS-related environmental and health impacts (Stoiber et al., 2020).

2.10 Summary

The most important findings and key recommendations based on literature review are:

- Plastic waste is a major contributor to environmental pollution. When plastic products are discarded improperly, they often end up in landfills, oceans, rivers, and other natural habitats. This pollution can harm wildlife, disrupt ecosystems, and degrade the environment.
- Plastics do not biodegrade but instead break down into smaller pieces called microplastics that can be ingested by marine organisms and eventually enter the food chain, including seafood consumed by humans. The long-term health effects of ingesting microplastics are still being studied, but it is a growing concern.
- Improper disposal and poor waste management can lead to plastic accumulation in soil. As plastics slowly degrade, they can release harmful chemicals into the soil, affecting plant growth and potentially entering the food chain when consumed by animals or humans.

- Plastic recycling rates are generally low, and many plastic products are used only once before being discarded. The sheer volume of plastic waste poses significant worldwide challenges for waste-management systems.
- Addressing these plastic-related problems requires a multi-faceted approach, including improved waste management, increased recycling efforts, sustainable alternatives to single-use plastics, and individual actions to reduce plastic consumption and promote responsible disposal. Governments, industries, and individuals all play crucial roles in finding solutions to mitigate the harmful impacts of plastic on both humans and the environment.
- While several types of asphalt mixtures exist, recycled plastic addition is usually studied on dense graded asphalt or asphalt concrete.
- Incorporating recycled plastic wastes into asphalt mixtures improved engineering performance parameters such as stiffness, rutting resistance, and fatigue resistance.
- Recycled PET is suitable for use in bituminous mixtures used in road making. Incorporating PET can enhance flexible pavement’s stability, stiffness, and viscosity, thereby improving its resistance to rutting, thermal cracking, and fatigue damage.
- When LDPE is melted, it alters the bitumen rather than replacing the aggregate, increasing binder content in specimens with a high LDPE content, a factor that should be considered in each mix design.
- Incorporating plastics into asphalt through the wet process may cause two potential concerns, including phase separation and low-temperature performance of the binder blends. Plastics with high melting points tend to exaggerate such concerns. The dry process is applicable for all plastic types to enhance asphalt pavements' rutting and moisture resistance. Plastics with high melting points are usually applied as aggregate substitution, whereas plastics with low melting points could form a thin film to increase the adhesion among asphalt, plastics, and aggregates.
- Some recycled plastics yielded conflicting performance measures, e.g., HDPE’s effects on rutting and fatigue resistance, PP’s effect on stiffness and rutting resistance, and PS’s effect on rutting resistance. More research is needed in this area.
- Proprietary asphalt binders offer enhanced durability, improved temperature susceptibility, superior rut resistance, and enhanced aging resistance.
- Proprietary additives such as anti-stripping agents and rejuvenators can be used to improve asphalt-aggregate adhesion, moisture resistance, and pavement aging properties. Companies sometimes develop proprietary binders with specific performance characteristics tailored to meet the demands of different pavement applications.
- Concrete workability increases by up to 50% of coarse recycled plastic aggregates used, but workability decreases beyond this level. Workability with fine recycled plastic aggregate depends on various factors.
- Plastic aggregate significantly increases concrete air content due to irregular shape, immiscibility, and hydrophobic nature of plastic. Increasing plastic aggregate content reduces concrete density, primarily when larger and flakier particles are used.
- Compressive strength generally decreases with increasing plastic aggregate content, although some studies show an increase at low replacement levels. When using plastic aggregate fiber, compressive strength decreases with increased fiber content and length due to increased air content. The elastic modulus decreases linearly with increasing plastic aggregate content but less than the drop in compressive strength. Further research is required to enhance these characteristics in this context.

- While the flexural/splitting tensile strength of plastic aggregate concrete decreases, at moderate replacement levels (below 20% of waste plastic fiber), an increase in flexural/tensile properties can be achieved.
- The ductility of concrete significantly increases with up to 50% plastic aggregate content, but the fracture energy decreases with higher plastic aggregate content. The addition of waste plastic increases shrinkage, water absorption, and chloride ingress, lowering concrete's thermal conductivity.
- Guidelines on efficiently using recycled plastic in transportation infrastructure systems are required. Guidelines for using plastic aggregate in concrete that define optimum content, size, and shape are also required.
- Additional investigations must be conducted to explore the extended durability of plastic aggregates within the concrete and associated environmental implications. Further studies are also necessary to examine factors that affect plastic aggregates, such as treated aggregates, aggregate morphology, and size, to enhance assurance in using plastic aggregates in concrete.
- Uniform mixing of plastic has been mainly used. If the recycled plastic were to be added horizontally or vertically in layers or an inclined manner, subsequent tests would be necessary to measure and determine the results. In this regard, further studies are required to find the optimum size and shape of recycled plastic and its percentage content and assess the durability and aging properties of recycled plastic.
- Large-scale testing is required to ascertain how the boundary effects can influence the outcomes of the tests.
- Large-scale testing is also necessary to evaluate the environmental impact, biodegradability, and sustainability of transportation infrastructure systems that have been modified with recycled plastic, especially in terms of their long-term behavior.

Chapter 3: Survey, Interviews, and Characterization of Plastic Materials

In this chapter, promising recycled plastic materials were identified and procured through a survey and interviews.

3.1 Survey Development and Interviews

A survey and interview questionnaire based on complexity were prepared in consultation with the TAP, with both closed-form and open-ended questions. The questions ranged from revealing an understanding of the recycling processes of plastic waste to collecting practical knowledge and experience on using recycled plastic materials.

The first part of the survey was executed with all potential participants listed. However, the second part, which includes interviews, has been executed only with selected potential participants (identified through consultation with TAP) who had specific reasons for achieving the project objective and were, therefore, more willing to participate. This mixed method allowed the research team to collect valuable new information from survey participants. Two surveys are presented in Appendix A.

The recycled plastic materials will be characterized into seven categories under ASTM D7611/D7611M-21 (2022), and the shape forms of those materials will be characterized into three groups based on reprocessing types through the recycling chain: (1) shredded plastics (sometimes referred to as chips or flakes) that obtain their form after the shredding process; (2) pellets (also referred to as granules) that are formed after extrusion and pelletizing processes; and (3) plastic powders, the finest and smallest form of waste plastics.

A list of potential proprietary recycled plastic producers is presented in Table 3.1, and Minnesota-based recycled plastic producers and other potential proprietary recycled plastic producers are presented in Tables 3.2 and 3.3, respectively.

Table 3.1 The Proprietary Recycled Plastic Producers

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
1	Macrebur (Southern California)	U.S.	Website: https://www.macrebur.com/ E-Mail: info@macrebur.com Tel.: 6199942501	Pelletized industrial and postconsumer plastic bottles and bags	MR6 & MR8	MR6 and MR8 are both manufactured from a mix of polymers	MR6 is used where traditionally polymer modified bitumen's (PMBs) are specified. This might be on motorways, heavy-duty base courses or where surface courses are subject to heavily loaded traffic. MR6 provides a direct replacement to virgin polymer, which is used in the production of PMB. MR8 is used where unmodified binder (liquid asphalt) is normally specified, for instance, in all base, binder and surface course asphalt material on standard traffic roads, footways, etc. MR8 is used as a direct replacement for neat binder used in asphalt and is typically dry mixed at an asphalt plant.	

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
2	Elvaloy by Dow	U.S.	Website: https://www.dow.com/en-us Multiple branches in U.S. https://corporate.dow.com/en-us/locations.html	An asphalt binder additive produced from waste shopping bags	Recycled polymer modified asphalt (RPMA)	Post-consumer recycles content (PCR) (The base asphalt binder is modified by adding the PCR with ELVALOY™ RET to the asphalt.)	Sustainable roads with excellent performance, long service life, and lower life-cycle costs compared to conventional, neat asphalt.	ELVALOY™ 5170 / ELVALOY™ 4170 Copolymer: A Reactive Terpolymer (RET) that can be used to modify the properties of asphalt used in paving. It has been specially designed to give the best performance and value while minimizing safety hazards on road.
3	NeoPave (formerly G5) by Technisoil Industrial	U.S.	E-Mail: info@technisoilind.com Tel.: 4711452	A urethane polyol-based binder with waste plastic bottles	-	Recycling 100% of the existing road is in place, and approximately 150,000 plastic bottles are recycled per lane mile.	Roads recycled with Neo possess the strength of concrete and the flexibility of asphalt. Neo enhanced pavement lasts 2 – 3 times longer than asphalt, has 5X the tensile strength of asphalt with greater flexibility. Neo also helps eliminate rutting and provides extremely high reflective cracking resistance while delivering at least 50% life-cycle savings to taxpayers.	Neo is used to modify a common process called Cold In-Place Recycling. We mill up failing asphalt, crush and resize it, mix it with Neo, and immediately repave it. We eliminate the need to haul 84 trucks of asphalt out/in and return to traffic within hours instead of days or even weeks. https://neopave.com/

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
4	Altisora	U.S.	Website: https://www.osti.gov/biblio/1756319 E-Mail: info@altisora.com	Salvaged ocean fishing net fiber additive to modify asphalt	AltiFiberPLUS	Creating an asphalt additive based on ocean plastic, namely ocean bound fishing nets	AltiFiberPLUS, is a formulation from discarded fishing nets that improves road strength and durability. AltiFiberPLUS has shown to improve rutting and cracking of commercial asphalt mixes by 44% and 16% respectively. Planning to introduce the next ocean plastic asphalt additives in the family: AltiBinder and AltiFiber	
5	Advanced Materials Group (NVI)	U.S.	Website: https://www.nviamg.com/products E-Mail: info@nviamg.com Tel.: (800)583-3892	Asphalt binder additives and concrete aggregate replacements blended from recycled plastic polymers		Recycled Hybrid-Polymer/Plastic -Based additives	Concrete: Lightweight concrete: faster, cheaper, more per truckload Asphalt: ● Decrease Hamburg rutting by up to 50% ● Increase pavement life by up to 50%	

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
6	Huesker International	Germany	E-Mail: marketing@HUESKER.com Tel.: 800 942 9418	Asphalt reinforcement grid as well as geogrids for subgrade soil and aggregate base reinforcements	Fortrac and HaTelit geogrids (various types)	Made from 100 % recycled PET bottles	Fortrac Geogrid for soil reinforcement: Highly resilient, flexible geogrid with a proven track record in soil reinforcement. HaTelit Asphalt Reinforcement Geogrid: allows a significant extension of renovation intervals. Thus, the useful life of the traffic areas is extended. Because of the associated reduction in maintenance costs, HaTelit offers a very economical solution for the repair of road surfaces.	Fortrac: https://www.huesker.us/geosynthetics/products/grids/fortrac/ HaTelit: https://www.huesker.us/geosynthetics/products/grids/hatelit/
7	FORTA	U.S.	Website: https://forta-ferro.com/ Email: info@fortacorp.com Tel: 724-458-5221	fiber for concrete reinforcement	Fiber	Various Materials	Concrete reinforcement	Some Products FORTA-FERRO FERRO-GREEN (Made of recycled polypropylene and copolymer macro fibers)
8	NecoTECH	U.S.	Website: https://necotech.com/ Address: Delaware Entrepreneurial Center Ohio Wesleyan University 70 S Sandusky St, Suite 210 Delaware, OH 43015 Tel: 833-444-NECO (6326)	Sustainable Materials	Asphalt Concrete Plastic Building materials	Waste Materials	Infrastructure and building materials Pavement	Some Products NecoPlastics NecoWaste NecoCrete NecoPave

Table 3.2 The Minnesota-based Recycled Plastic Producers

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
1	Gopher Resource	U.S.	Website: https://www.gopherresource.com/ Address: 3385 Highway 149, Eagan, MN 55121 Tel: (651) 454-3310, (800) 354-7451	lead alloys plastic pellets Recycled polypropylene converted into high-grade, competitively superior resins (comparable to virgin plastic)	Metallic lead and lead alloys polypropylene copolymer	Used battery cases and other PP containers	Process and recycle spent automotive, stationary and industrial lead batteries Safely dispose of non-recyclable waste following strict environmental regulations.	-
2	Poly Plastics Inc.	U.S.	Website: https://www.recycleyourplastic.com/ Address: 26612 Fallbrook Ave Wyoming, MN 55092 Tel: (651) 462-2880	Plastic resin	PP, HDPE, PVC, LDPE, LLDPE and ABS resins	Recycled Materials	-	-

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
3	Chesapeake Materials	U.S.	Website: https://cmsplastic.com/plastic-recycling-minnesota/ Address: 1157 Mayo Road Suite 310 Mayo, MD 21106 Tel: +1 (443) 219-3411 Email: sales@cmsplastic.com	Plastic Materials	HDPE crate repro 6 to 8 melt with .960 mixed color HDPE frac melt repro .4 to .7 with .956 for black HDPE Pallet regrind 5 plus melt LDPE rolls with print LDPE repro PP Injection grade regrind MC for black 8 to 20 melt PP repro made to spec from a frac melt up to a 50 melt PP nonwovens PET purge regrinds clear and MC	Recycled Materials	HDPE jugs/ bottles natural and color HDPE buckets HDPE pallets HDPE crates HDPE Post Consumer bales HMW barrels HMW pallets HMW dunnage trays HDPE films PP buckets PP pallets	-
4	SMI Strategic Materials, Inc	U.S.	Website: https://www.smi.com/ Address: 195 Minnehaha Avenue E Saint Paul, MN 55130 Tel: 281-647-2700 Email: info@smi.com	Plastic Materials	Plastic Container Glass fibers Fillers	Glass and Plastic Recycling	Recycled plastic resin	Strategic Materials recycles plastic through NexCycle.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
5	Choice Plastics, Inc.	U.S.	Website: https://choiceplastics.com/ Address: 5338 Shoreline Drive Mound, MN 55364 Tel: 952-472-3070 Email: Dan Mayer dan.mayer@choiceplastics.com	Plastic Materials	ABS Acrylic Ethylene (HDPE, LDPE, LLDPE, HMW) Polycarbonate Polypropylene PVC (Rigid, Flex, Blister) Reprocessed Pellets Regrind Styrene (HIPS, GPPS) TPE TPO (Filled, Unfilled) Virgin Resin (Prime, Wide Spec, Off Spec)	Recycled Materials		Offering a wide variety of certified virgin resin and post-industrial commodities, to include reprocessed pellets, regrind, loose scrap, and sheet material.
6	EXCESS POLY	U.S.	Website: https://excesspoly.com/ Tel: 1-888-400-5537 Email: info@excesspoly.com	Plastic Materials	Plastic Materials	Recycled Materials	Specializing in close-loop Plastic Recycling Services for all types of industrial and manufacturing needs.	An Industrial Plastic Recycling Company

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
7	Alliance to End Plastic Waste	U.S.	Website: https://endplasticwaste.org/en Email: info@endplasticwaste.org	Develop strategy to recycle plastic in various countries	-	-	Recycle Market app	Focus on enhancing waste management capacity and capability by improving collection, sorting, processing, and recycling systems, especially in underserved regions
8	REO Plastics Inc	U.S.	Website: https://www.reoplastics.com/ Address: 11850 93rd Ave N, Maple Grove, MN 55369 Email: (763) 425-4171	Plastic Materials	Plastic Materials	Recycled Materials	Plastic Injection Molding Value Added Services	-
9	The Plastic Resource	U.S.	Website: https://www.plasticresource.com/ Address: 1526 Randolph Ave, St Paul, MN 55105 Tel: +1-651-702-9243 Email: sales@plasticresource.com	Plastic Materials	Plastic cards Key tags and Combos Careers and sleeves	Recycled Materials	-	-
10	Reprocessed Plastics, Inc.	U.S.	Website: https://www.gipo-rpi.com/ Address: 8301 County Hwy 82, Garfield, MN 56332 Tel: (320) 834-2451 Email: mike@rpisheets.com	Plastic Materials	Recycled HDPE Sheets	Recycled Materials	-	-
11	Myplas USA, Inc.	U.S.	Website: https://myplasusa.com/ Address: 19850 S Diamond Lake Rd, Rogers, MN 55374 Tel: +1(763)328-0000 Email: info@myplasusa.com	Plastic Materials	Recycled Polyethylene	Flexible packaging and films	-	-

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
12	New Plastics Plus	U.S.	Website:https://www.newplasticsplus.com/ Address: 12707 42nd St NE, St Michael, MN 55376 Tel: (763) 210-1116	Plastic Materials				Plastic fabrication company in St. Michael, Minnesota

Table 3.3 Other Potential Recycled Plastics Facilities

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
1	Mid America Recycling (MAR)	U.S.	2742 East Market Street, Des Moines, IA 50317 515-265-1208/ info@midamericarecycling.com http://www.midamericarecycling.com/	Paper Metal Plastics	Recycled Plastics PDE, HDPE	Various types of Waste Plastics	Comprehensive, multi-material usage	Largest recycling facility in Iowa and offers both residential and commercial single stream processing capabilities. Four grades of plastics, including large volumes of PETE, LDPE, HDPE and PVC are sorted, cleaned and processed into large bales for shipment to both domestic and international recyclers. In addition to the single stream recycling facility in Des Moines, MAR offers the following services in the locations: Sioux City, IA - Granulate plastic/Cedar Rapids, IA - Baling aluminum, plastic, granulate plastic/Sioux Falls, SD - Baling aluminum and plastic.
2	Cedar Rapids/Linn County Solid Waste Agency	U.S.	https://www.solidwasteagency.org/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	An intergovernmental agency operating two facilities in Linn County. Most plastic material types except PS are accepted for recycling.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
3	Clinton County Area Solid Waste Agency	U.S.	4292 220th St., Clinton, IA 52732 563-243-4749/ ccaswa@ccaswa.com http://ccaswa.com/home/4089824	Landfill solid waste management services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	An intergovernmental agency serving the County of Clinton for solid waste disposal and recycling programs. Plastic food containers from most plastic material types are accepted for recycling.
4	Metro Waste Authority	U.S.	300 East Locust Street, Suite 100, Des Moines, IA 50309 515-333-4430/ jme@mwatoday.com (to Judi Mendenhall, Director of Recycling & Diversion) https://www.mwatoday.com/	Versatile Recycling Services	Recycled Plastics HDPE, LDPE	Various types of Waste Plastics	Comprehensive, multi-material usage	An independent government agency to manage the landfill for the Polk County area Has a plan to building its own MRF.
5	Cedar Poly, LLC	U.S.	200 Commerce Blvd, Tipton, IA 52772 563-886-2811 http://cedarpoly.com/	Versatile Recycling Services	Recycled Plastics HDPE, LDPE	Various types of Waste Plastics	Comprehensive, multi-material usage	An Iowa based the recycling and plastics-processing company Has processing capabilities for plastics, including grinding, washing and pelletizing HDPE, LDPE and PPS.
6	Envirovision Technologies, LLC	U.S.	1959 South 21st Street, Clinton, IA 52732 855-333-0133/ info@evtusa.com http://evtusa.com/index.html	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	The Iowa office of Envirovision Technologies, LLC. Provide injection grade regrind and reprocessed materials including HDPE, PP, PETE, and LDPE.
7	MDK ZeroLandfill	U.S.	625 Klenske Avenue, New Hampton, IA 50659 641-394-2129 https://mdkzerolandfill.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	A supplier for recycled plastics, metals, textiles and paper.

No.	Company Name	Location	Contact Info	Products	Product Type	Raw Materials	Applications	Others
8	Quincy Recycle	U.S.	6281 N. Gateway Dr., Marion, IA 52302 319-382-2132 ccrawford@quincyrecycle.com (to Chad Crawford, General Manager of IA plant) https://www.quincyrecycle.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	Has plastic recycling processing capabilities of most of plastic type.
9	Plastic Recycling of Iowa Falls, Inc.	U.S.	10252 Hwy. 65, Iowa Falls, IA 50126 641-648-5073/ info@plasticrecycling.us http://plasticrecycling.us/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	A manufacturing company for recreational/traffic control/lumber products from recycled plastic.
10	Renewablade	U.S.	1200 Prairie Dr. Bondurant, IA 50035 515-778-4504 Bian Meng, 515-809-9717, brianm@renewablade.com Nick Wylie, Partner, 515-577-2011, nick@jpettiecord.com http://www.renewablade.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	The survey was not distributed due to its business. A company processing wind turbine blades into glass fibers and composite fillers
11	Chesapeake Materials Services	U.S.	https://cmsplastic.com/	Versatile Recycling Services	Recycled Plastics PET	Various types of Waste Plastics	Comprehensive, multi-material usage	-

The first part of the survey was sent to more than 30 companies and suppliers, mainly located in Minnesota. The responses from these companies and suppliers to the first question in the general category indicate that there are some material-recovery facilities (MRF) that recover recyclable materials from municipal solid waste, some recycled plastic suppliers (RPS) that reprocess pre-treated plastic from MRF into recycled plastic products, and some facilities in both categorizations.

Since four companies and suppliers responded to the first part of the online survey by showing interest in responding to the second part, the research team conducted an online meeting with the representatives of these companies.

During the online meeting with company representatives, the research team asked questions related to the company's products, their types and shapes, disposal methods and capacity for dealing with different plastic types, procedures for waste plastic processing, challenges related to plastic-waste recycling, environmental concerns about products, and sustainability metrics.

The survey results show that the responding companies and suppliers produce various types of recycled plastic including PET, HDPE, LDPE, PVC, PP, and PS. Figure 3.1 shows that 33% of responding facilities and companies recycle PET, 17% recycle PP, 17% recycle PS, 17% recycle HDPE, and 17% recycle LDPE. None of these facilities or companies recycles V or PVC or other types of plastic (resins, acrylonitrile butadiene styrene, nylon, etc.).

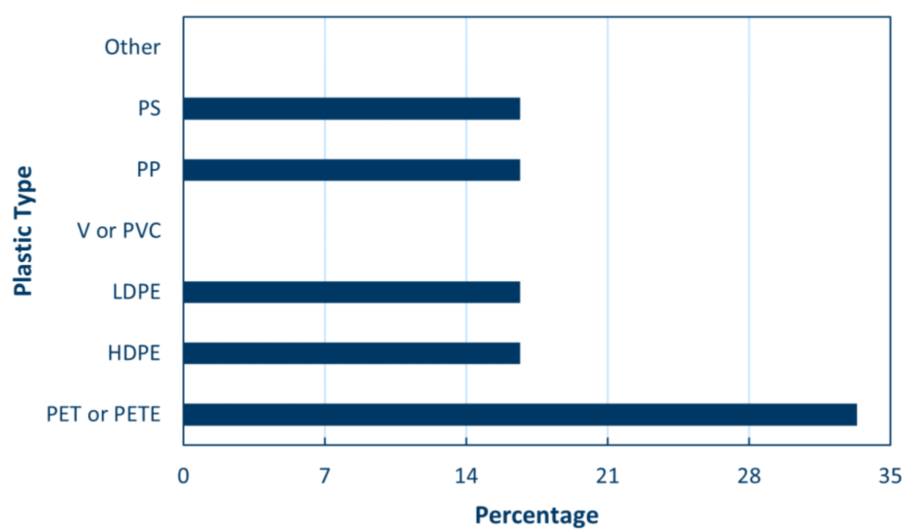

Figure 3.1 Type and percentage of plastics produced/recycled by facilities and companies

As shown in Figure 3.2, most responding facilities and companies produce recycled plastic products in strip (33%) and flake (33%) forms, while 17% produce plastics in pellet form and the remaining 17% manufacture them in other shapes. All responding facilities and companies customize the size and shape of their recycled plastic products. Based on the survey results, recycled plastic pellets from FORTA and NVI are mainly used to produce fibers for asphalt and concrete pavement reinforcement. While these facilities and companies produce some recycled plastic products in percentages ranging from zero to 100%, they are mainly made of 100% recycled plastic.

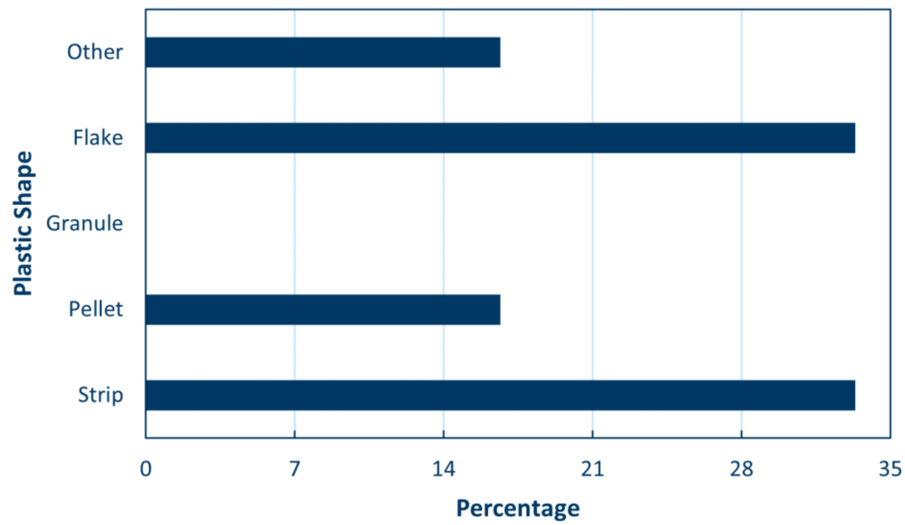

Figure 3.2 Shape and percentage of plastics produce/recycle by facilities and companies

As shown in the survey results, all companies and suppliers employ quality control/quality assurance (QC/QA) tools for specifications of raw materials and finished products, plant documentation, equipment and process, standardized sampling plans, laboratory testing, etc., to control/assure the quality of recycled plastic products during manufacturing. As shown in the survey results, contaminations such as residual food and liquid in collected plastics can result in high recycling or reprocessing costs and technical difficulties in recycling and reprocessing plastic. Additionally, a limited market size and a lack of clients pose significant challenges that most facilities and companies face when engaging in plastic-waste recycling and reusing.

3.2 Potential Companies and Suppliers

The following subsections investigate in detail leading companies, including the NVI Advanced Materials Group, NewRoad, FORTA LLC, and Regen Fiber, which produce fibers for asphalt and concrete pavement reinforcement, and the Technisoil Industrial (Neopave) company that produces sustainable pavements made of recycled plastic. This information is based on data available on company websites and from the research team's interviews with company representatives.

3.2.1 NVI Advanced Materials Group

One of the main products of NVI Advanced Materials Group is called NewRoad®, a hybrid polymer additive that improves the internal bonding of an asphalt mixture to achieve 50% longer life, lower rutting and cracking, and significantly lower life-cycle costs. This product, made from 100% recycled PET plastic waste, is used by large commercial accounts, including truck and automotive dealers, retail parking lots, County, City, and other state DOT roads, federally-funded highways, and special applications in which strength and high performance are critical. NewRoad® increases both strength and moisture resistance and decreases rutting and cracking. It has been lab and field-tested for the past five years by multiple independent and university labs, including the National Center for Asphalt Technology (NCAT) at Auburn University, the premier testing facility in the USA. The NVI Advanced Materials Group company provided some of the significant results of NewRoad® performance evaluation shown in Figures 3.3 to 3.5.

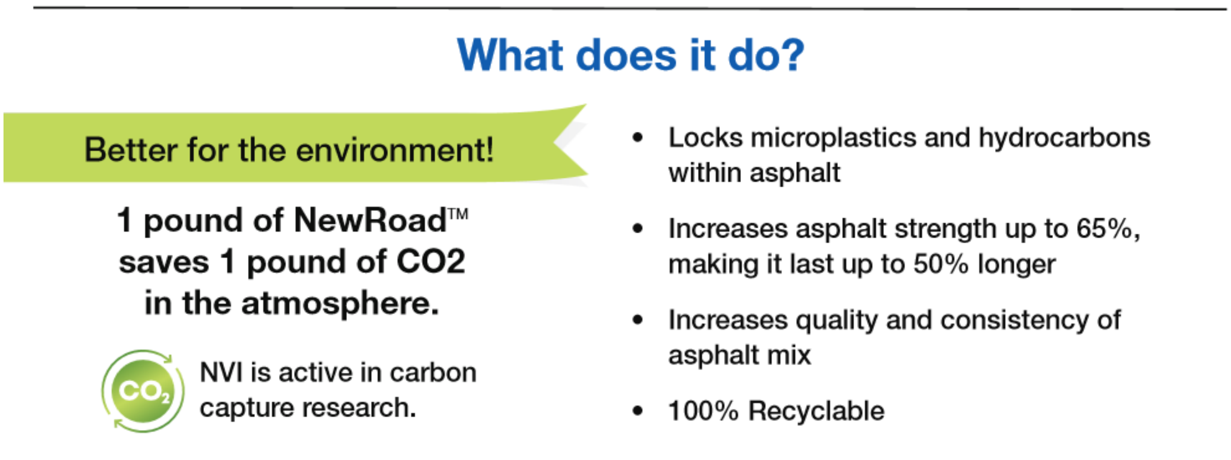

Figure 3.3 NewRoad environmental benefits (NVI Advanced Materials Group, 2023)

Figure 3.4 NewRoad gives asphalt longer life (NVI Advanced Materials Group, 2023)

Figure 3.5 NewRoad® performance in asphalt pavements (NVI Advanced Materials Group, 2023)

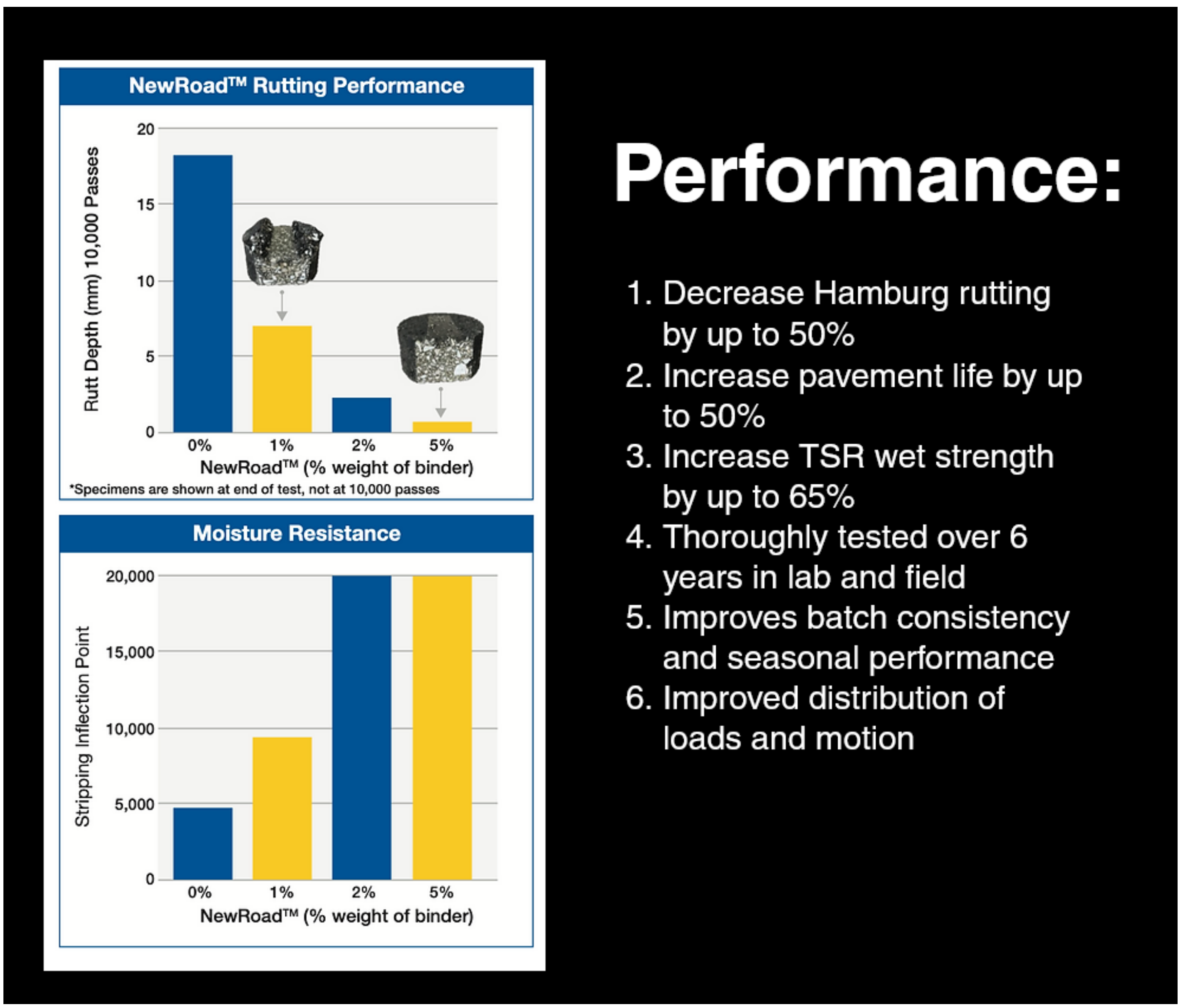

Figure 3.6 NewRoad® performance based on Hamburg tests in asphalt pavements (NVI Advanced Materials Group, 2023)

The NVI Advanced Materials Group has recently developed products similar to NewRoad® for a concrete product called NewRoad™ Concrete. NewRoad™, whose additives are made of 100% recycled PET plastic waste, scientifically designed and highly engineered blends of recycled industrial, consumer, and structural polymers, all saving plastics from deposit in landfills and oceans while improving concrete performance and longevity. NewRoad™ Concrete additive brings new capabilities to concrete while significantly reducing its carbon footprint and emissions. Precisely engineered and manufactured NewRoad™ aggregate replacement produces lightweight, high tensile, and compression strength mixes that hydrate quickly, absorb vibration and sound, and add insulation R-value to walls, floors, ceilings, and roofs, all while repurposing waste plastic and industrial polymers. While reducing water intrusion, cracking, mold formation, and sound conduction while maintaining structural strength, fire ratings, and increasing resistance to wide temperature variations due to global warming events, NewRoad™ provides environmental protection, energy efficiency, structural performance, and cost savings. Some of the main results of NewRoad® concrete performance evaluation are provided in Figure 3.5 courtesy of the NVI Advanced Materials Group.

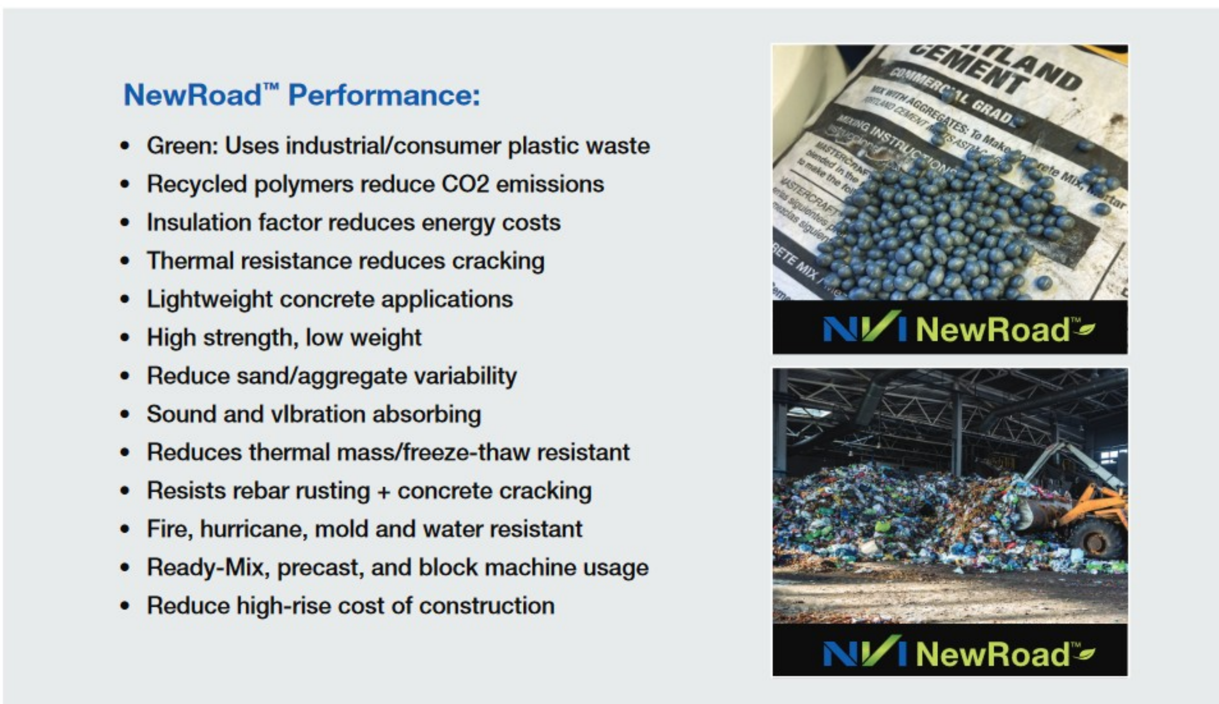

Figure 3.7 NewRoad® concrete performance evaluation results in concrete pavements (NVI Advanced Materials Group, 2023)

NewRoad® captures microplastics and hydrocarbons and contains them within the asphalt, significantly reducing the volume of contaminants in the surrounding wetlands and environment. According to some environmental tests performed by NVI Advanced Materials Group on asphalt pavements reinforced with NewRoad®, the microplastic count from an asphalt mixture is reduced after including NewRoad® in the mixture because of better bonding within the asphalt mixture due to its use.

NewSand® is an engineered blend of recycled polymers manufactured by NVI Advanced Materials Group, designed as a sand replacement for construction materials (NVI Advanced Materials Group, 2023). The product is a powder-based aggregate with particles ranging from 0.3 to 2.0 mm, composed of over 95% polyethylene, and featuring a proprietary blend of additives. The material has specific handling considerations, including potential static charge accumulation and a slipping hazard when spilled, and can be used safely when proper precautions are taken.

3.2.2 FORTA

FORTA LLC provides various types of fibers, including Macro Synthetic, Micro Fibrillated, Micro Monofilament, Specialty Fibers, Flowable Fill, and Fiber Feeders. FORTA FERRO-GREEN fiber used for concrete pavement reinforcement is made of recycled plastic. FORTA FERRO-GREEN fiber and its physical properties are presented in Figure 3.6.

PHYSICAL PROPERTIES

Materials: Virgin Copolymer and recycled polypropylene blend
Form: Macro-monofilament/fibrillated-net blend
Specific Gravity: 0.91
Tensile Strength: 83-96 ksi. (570-660 MPa)
Length: 0.75" (19mm), 1.5" (38mm), 2.25" (54mm)
Color: Gray/dark gray blend
Acid/Alkali Resistance: Excellent
Absorption: Nil
Compliance: A.S.T.M. C-1116

Figure 3.8 FORTA FERRO-GREEN fiber for concrete made of recycled plastic and its physical properties (FORTA FERRO-GREEN fiber, 2023)

FORTA FERRO-GREEN comprises 100% recycled polypropylene fibrillated (network) fibers and a high-performance twisted-bundle macro-monofilament fiber designed to mix, distribute, and finish well in concrete mixes. This fiber combination offers a variety of desirable benefits to previous concrete pavement applications, including increased strength, toughness, freeze-thaw resistance, and durability. FERRO-GREEN toughens previous concrete applications such as driveways, curbs, sidewalks, commercial parking lots, and pavements. The three-dimensional distributed non-corrosive macro fiber blend offers one of the few methods for adding proper toughness reinforcement to previous cross-sections without reducing porosity. FERRO-GREEN also increases resistance to freeze-thaw damage and raveling while preserving the plastic and hardened concrete void structure. FERRO-GREEN is generally dosed in a range between 0.17% and 0.5% by volume of concrete, or 2.5 lb. to 7.5 lb. per cubic yard of previous concrete, depending on the desired level of additional toughness and crack control required for the application. The main benefits of using FORTA FERRO-GREEN fiber in concrete are improved quality, decreased construction time, long-term cost savings, and reduced minimized joints.

3.2.3 Technisoil Industrial (Neopave)

Technisoil Industrial (Neopave) produces a product called Neo (formerly G5), a brand-new material formulated to divert plastic from a waste stream at a rate and value capable of driving powerful changes at scale. Neo diverts a whopping 150,000 plastic bottles per lane-mile from single-use, post-consumer waste into long-term solutions, providing a 90% reduction in greenhouse gas emissions with zero leaching or other negative impact on water, air, or soils. Neo is used to modify a common process called Cold In-Place Recycling. Technisoil Industrial (Neopave) company mills up failing asphalt, crushes and resizes it, mixes it with Neo, and immediately repaves with it, eliminating the need to haul 84 trucks of asphalt out/in, and also offers a return to traffic within hours instead of days or weeks.

As shown in Figure 3.7, roads recycled with Neo possess concrete strength and asphalt flexibility. Neo-enhanced pavement lasts 2-3 times longer than asphalt and has 5X the tensile strength of asphalt while offering greater flexibility. Neo also helps eliminate rutting and provides exceptionally high reflective cracking resistance while delivering at least 50% life-cycle savings to taxpayers.

3.2.4 Dow

DOW, a leading materials science company, produces a range of polyethylene products, including High-Density Polyethylene (HDPE), Linear Low-Density Polyethylene (LLDPE), and Low-Density Polyethylene (LDPE) (Dow, 2024). Their HDPE products are known for high strength, durability, and chemical resistance, making them suitable for demanding applications such as plastic bottles, containers, and piping systems. DOW's LLDPE products are designed for flexibility and tensile strength, which makes them ideal for flexible films, packaging materials, and stretch films. DOW's LDPE offerings are also valued for their flexibility and low-density structure, making them a popular choice for plastic bags, food wraps, and squeezable bottles. These polyethylene products from DOW are widely used across various industries, benefiting from the company’s advanced technologies and innovations.

3.2.5 REGEN Fiber

REGEN fiber produces sustainable materials by recycling composite waste, mainly focusing on wind turbine blades. REGEN Fiber is a 100% recycled reinforcement fiber used in concrete and asphalt applications, enhancing strength and durability while providing superior finishing results (REGENfiber,2024). The fibers are made from retired wind turbine components, creating a sustainable solution for construction materials. As wind energy continues to grow, the disposal of decommissioned wind turbine blades has become a significant environmental challenge due to their large size and the composite materials used in their construction. REGEN fiber addresses this issue by developing innovative products from recycled wind turbine blade materials. These products, including fibers and composites, are used in various industries, such as construction and automotive, offering a sustainable solution to reduce waste and promote circular economy practices. By repurposing wind turbine blades, REGEN fiber helps divert large amounts of material from landfills while contributing to developing eco-friendly products with a reduced environmental impact.

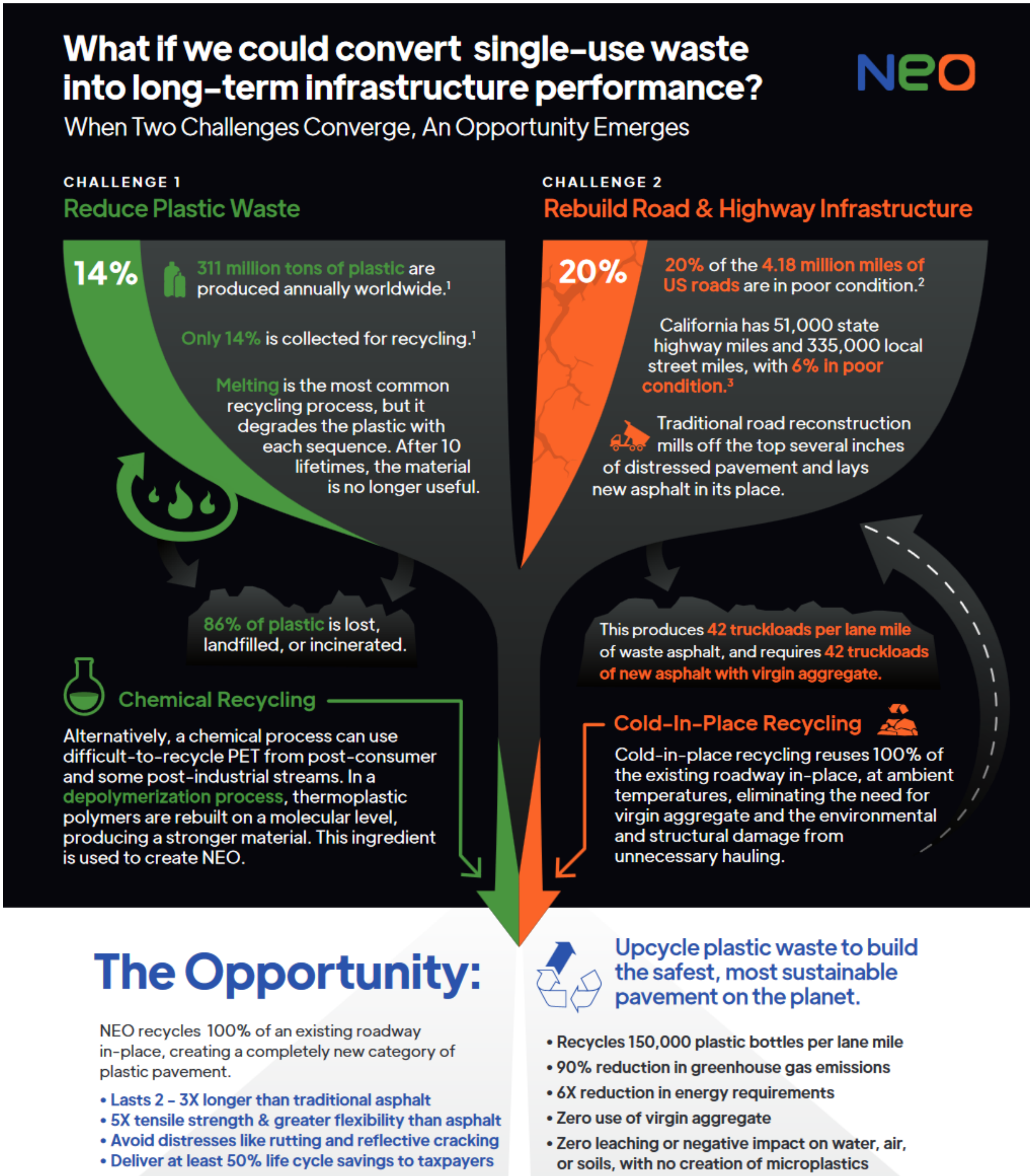

Figure 3.9 NEO performance (Technisoil Industrial (Neopave), 2023)

3.3 Summary

This chapter presented an overview of a survey and interview used to identify and characterize recycled plastic materials. While the survey was executed with the listed potential participants, the interview was executed with only selected potential participants, offering specific advantages for achieving the project objective. Promising recycled plastic materials produced by companies and suppliers to be used in the next chapter's feasibility study were further identified and procured through surveys and interviews. Answers to questions in the two parts of the survey helped with understanding the recycling processes of plastic waste the types and shapes of recycled plastic, and collected practical knowledge and experience on using recycled plastic materials. In this chapter, both an online survey (using a web-based survey tool like Qualtrics) and a telecommunications interview (using virtual meeting platforms like Cisco WebEx) of both proprietary and non-proprietary recycled plastic producers as well as Minnesota-based materials recovery facilities (MRFs) were investigated and were discussed. The main findings are as follows:

- According to the survey and interview results, an encouraging trend of using recycled plastic materials within transportation infrastructure systems has emerged, with the incidence of projects incorporating products made from recycled plastics on a discernible upswing. However, it has become evident that there is a great need for in-depth investigation into the long-term performance and durability of pavements constructed using such materials.
- Companies and suppliers engaged in recycled-plastic production encounter notable challenges, including issues such as contamination of collected plastics arising from residual food and liquid remnants, relatively high costs associated with plastic recycling and reprocessing, technical complexities inherent to recycling and reprocessing plastics, and the constraint of limited market size leading to a dearth of clientele.

Chapter 4: Conduct Feasibility Study of Using Plastic Waste Within Asphalt Roadway Paving

This chapter aims to evaluate incorporating post-consumer recycled (PCR) plastics into a typical MnDOT asphalt mixture. Incorporating PCR plastics into asphalt mixtures is typically accomplished by two processes, either wet or dry. In the wet process, PCR plastic is incorporated directly into an asphalt binder. In the dry process, PCR plastic is added directly to aggregates or an asphalt mixture. The focus of this chapter for MnDOT was the wet process, and it did not include compatibilization (where additives or other forms of chemical modification are used to increase the compatibility between a waste plastic and an asphalt binder).

4.1 MnDOT Mixture Design & Materials

4.1.1 Mixture Design

The Technical Advisory Panel (TAP) members for the project selected the mixture design to be used for asphalt, as shown in Figure 4.1. The mixture selected was a dense-graded 9.5-mm (3/8") Nominal Maximum Aggregate Size (NMAS) mixture incorporating 28% Reclaimed Asphalt Pavement (RAP) and a PG58S-28 virgin binder. The total binder content of the mixture was 5.8% (4.3% virgin binder and 1.5% binder from the RAP). The mixture was identified and characterized as outlined by MnDOT Bituminous Mix Design Report #3A-2023-234 2360-SPWEA230 (Figure 4.1).

4.1.2 Asphalt Mixture Design Materials

The materials related to the mixture design were received from MnDOT in December 2023. Specifically, the following asphalt binder and aggregates were received:

- PG58S-28 Flint Hills Binder (2 x 1 Gallon Cans)
- ½ Inch Rock (2 x 5 Gallon Buckets)
- Manufactured Sand (1 x 5 Gallon Bucket)
- Sand (2 x 5 Gallon Buckets)
- Millings (1 x 5 Gallon Bucket) [Reclaimed Asphalt Pavement]

4.1.3 Post-Consumer Recycled (PCR) Plastics

Based on a discussion with the TAP members, it was approved to utilize PCR plastic sources used in a previous Massachusetts study (Abdalfattah et al., 2022). PCR plastic source #1 was a Linear Low-Density Polyethylene (LLDPE) obtained from Dow. PCR plastic source #2 was a 50% mixture of High-Density Polyethylene (HDPE) and 50% Low-Density Polyethylene (LDPE) obtained from EREMA. Each PCR plastic source was in pellet form, as shown in Figure 4.2. Each had melting points lower than a typical asphalt mixture production temperature range. Thus, each plastic should melt at normal asphalt mixture production temperatures.

DEPARTMENT OF TRANSPORTATION

Bituminous Mix Design Report
District 3A Materials Lab

3A-2023-234
2360-SPWEA230
Reviewed Date: 10/09/2023
Reviewed By: Thomas Boser

Beginning Test #: 301

Gyratory, Wear Course, 1/2" aggr., <1 million ESALs, 3% voids

Plant #: BP064-MPM 4607
Located at: STAY PIT
Project Number:
Agency:

For Use with Asphalt Binder(s): B=PG 58S-28, E=PG 58H-28

TM # TM19-0022 Indicates a Gyratory Density of 148.1 (lbs/ft3) at 60 Design Gyrations.

Material Components

Source	Material	%	Total SpG	- #4 %	- #4 SpG
05054-Helmin	3139-1/2 in Rock	20	2.701	20	2.701
05060-Stay Pit	3139-1/2 in Rock	0	2.714	6	2.714
05060-Stay Pit	3139-Man Sand	10	2.730	87	2.730
05060-Stay Pit	3139-Man Sand Washed	0	2.723	80	2.725
05060-Stay Pit	3139-Sand	42	2.687	89	2.687
73006-Martin Marietta Quarry - St Cloud	3139-Sand Washed	0	2.657	96	2.657
Material coming from a project/roadway	3139-Millings	28	2.643	73	2.643
		SpG Total:	**2.682**	**SpG -#4:**	**2.680**

Mix Composite Gradation

Sieve Size	Proportion	Specification
1 1/2 Inch		
1 Inch		
3/4 Inch		
5/8 Inch		
1/2 Inch	100	97-100
3/8 Inch	94	85-100
#4	70	60-90
#8	57	45-70
#16	44	
#30	31	
#50	15	
#100	7	
#200	4.5	2.0-7.0

Mix Volumetric Properties

Parameter	Mixture	Specification
% Iso Voids	3.0	2.0 - 4.0
% Total AC	5.8	5.4
% New AC	4.3	
% New/% Total AC	74.1	70
Pbe	5.4	
Surface Area	29.4	
Adj. AFT	9.6	
VMA		
Use of Anti-Strip Required:	No	
Contains RAP:	Yes	
Contains RAS:	No	

THIS MIXTURE HAS BEEN REVIEWED FOR VOLUMETRIC PROPERTIES ONLY, IT DOES NOT ASSURE THAT FIELD PLACEMENT AND COMPACTION REQUIREMENTS HAVE BEEN MET.

Remarks: ADDING HELMIN ROCK

Tom Boser
Report Date: 10/09/2023

Figure 4.1 TAP approved MnDOT 9.5-mm mixture design

Source #1: LLDPE

Source #2: 50% HDPE + 50% LDPE

Figure 4.2 PCR plastics

4.2 Mixing Study to Determine Appropriate Mixing Time for Blending Plastic to Liquid Asphalt Using A Wet Process

4.2.1 Wet Process Mixing Procedure

In this study, each PCR plastic was incorporated directly into an asphalt binder using a wet process. This was achieved by using a high-shear mixer, as shown in Figure 4.3.

Figure 4.3 High shear mixer utilized for wet process mixing of PCR plastics into asphalt binder

The overall mixing process utilized for this study was developed with respect to the steps utilized in a previous study by Abdalfattah et al. (2022) to incorporate the same PCR plastics into asphalt binders using a wet process. The following steps were utilized for this study:

1. The virgin PG58S-28 asphalt binder was heated to its high mixing temperature of 310°F. This temperature was determined from viscosity test results of the virgin asphalt binder with respect to the mixture mixing viscosity range outlined in AASHTO T312 "Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor" (AASHTO, 2021).

2. The binder was placed in a heating mantel under the high-shear mixer. The heating mantel was utilized to maintain the binder temperature of 310°F throughout the mixing process.

3. The high-shear mixer was turned on. The shearing (mixing) speed was set to 3,000 rpm.

4. PCR plastic was slowly dropped manually (pellet-by-pellet) into the shear mixer vortex within the asphalt binder over 15 minutes. This is shown in Figure 4.4.

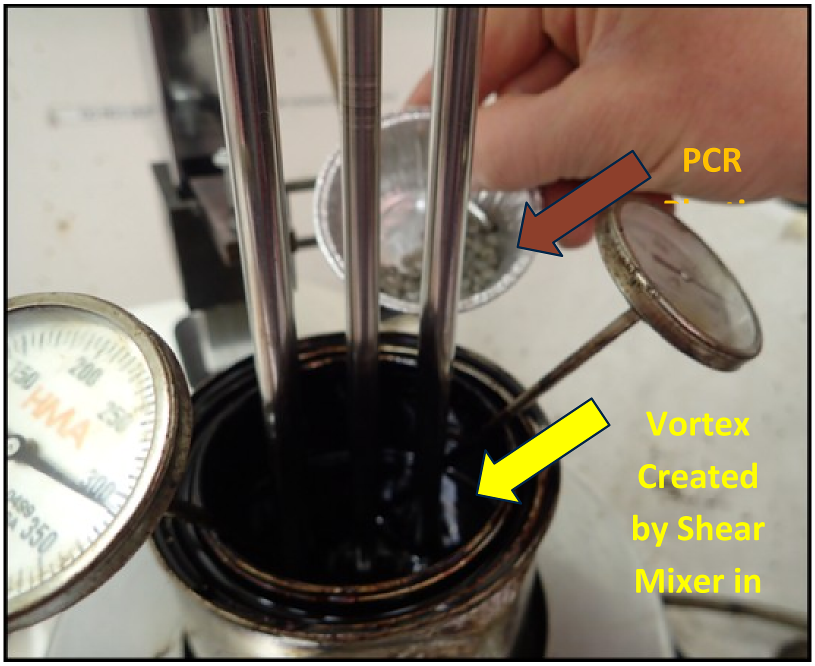

Figure 4.4 Manual addition of PCR plastic into asphalt binder

4.2.2 Determination of Appropriate Mixing Time

With the overall mixing process outlined, the remaining parameter to be determined was the appropriate mixing time for the wet process. In order to determine this time, an experiment was completed using the PG58S-28 virgin binder and PCR plastic source #2 (50% HDPE + 50% LDPE). The dose of PCR plastic was 1.5%, according to the weight of the virgin asphalt binder. The PCR plastic was introduced into the asphalt binder as noted in section 4.1.3.

Beginning immediately after introducing the entire PCR plastic dose (time = 0), two replicate 25-mm Dynamic Shear Rheometer (DSR) specimens were obtained from the binder using a glass rod as shown in Figure 4.5. There was no interruption to the mixing while obtaining these specimens. This process of obtaining DSR specimens continued for the following mixing times after introducing the PCR plastic dose:

t= 0 min. (Just after finishing adding plastic)
t= 15 min.
t= 30 min.
t= 45 min.
t= 60 min.
t= 75 min.

The DSR specimens collected are shown in Figure 4.6. As shown in Figure 4.7, each specimen was tested in the DSR at 58°C (corresponding to the high-performance Grade or PG temperature of the binder) to determine the asphalt complex shear modulus (G*) and phase angle (δ) with respect to mixing time. Testing was conducted in accordance with AASHTO T315 “Standard Method of Test for Determining the

Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)" (AASHTO, 2021). Values obtained for replicate specimens at each mixing time were averaged and are shown in Figure 4.8.

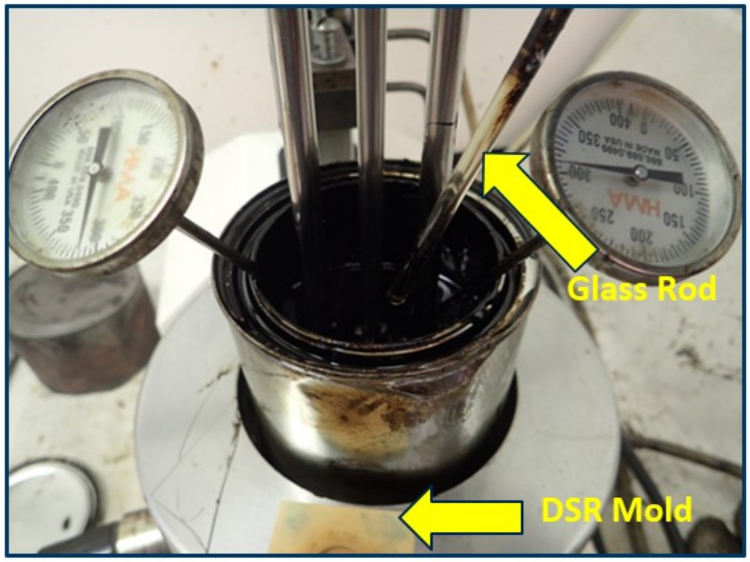

Figure 4.5 Obtaining DSR samples with glass rod during mixing

Figure 4.6 DSR specimens collected at various mixing times

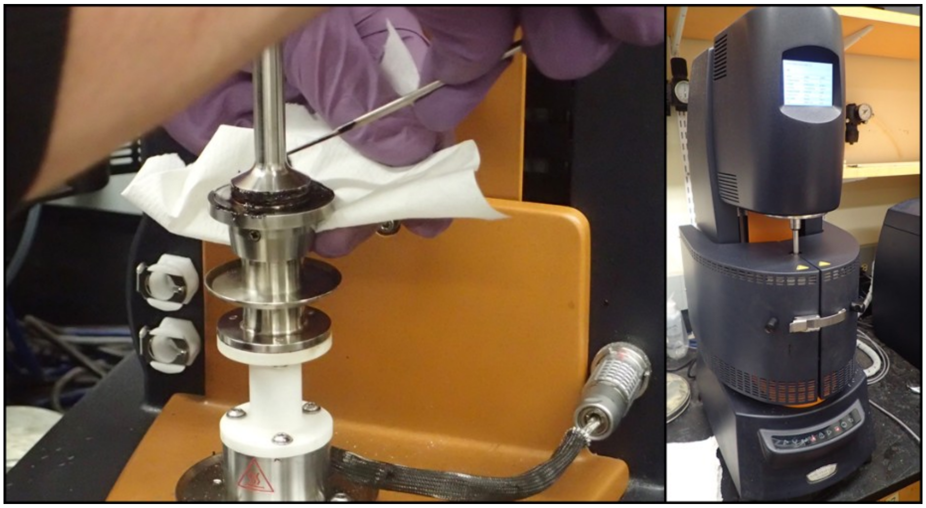

Figure 4.7 Testing of mixing study specimens (left) in the Dynamic Shear Rheometer (right)

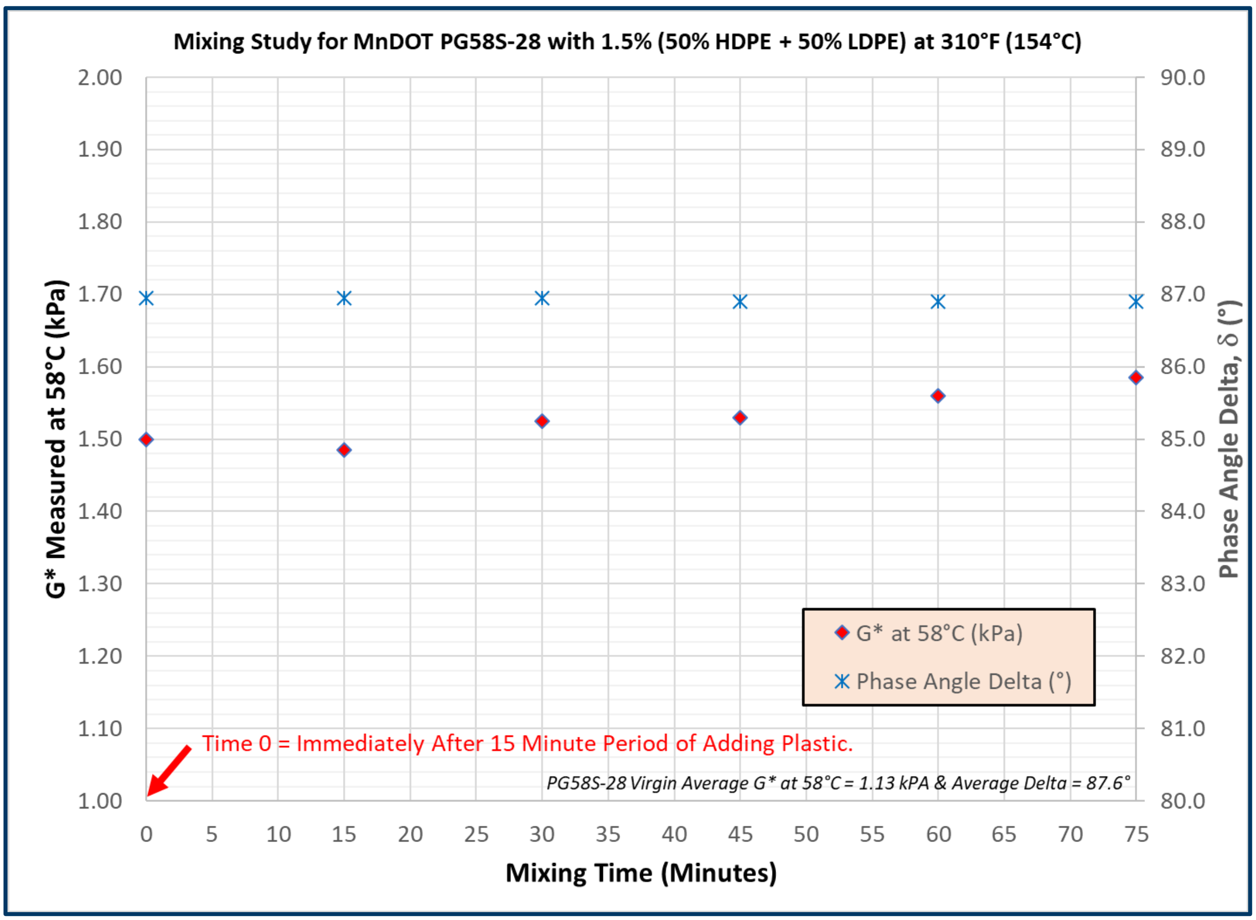

Figure 4.8 Mixing study test results from DSR testing

The appropriate mixing time was determined from this mixing study data. The mixing time is the time when the asphalt complex shear modulus (G*) and phase angle (δ) become constant (i.e. no significant change) thereby indicating that the plastic is completely melted and blended with the asphalt binder. As can be seen in Figure 4.8, the complex shear modulus and phase angle were nearly constant throughout the mixing process. Thus, 15 minutes was determined to be the appropriate mixing time as it was the minimum mixing time tested.

4.3 Asphalt Binder Performance Grade (PG) Determination

Performance grade (PG) testing was conducted on the MnDOT-supplied PG58S-28 virgin binder in accordance with AASHTO R 29 "Standard Practice for Grading or Verifying the Performance Grade (PG) of an Asphalt Binder", AASHTO M 320 "Standard Specification for Performance-Graded Asphalt Binder" and AASHTO M 332 "Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test" (AASHTO, 2021).

The same PG testing was conducted on each wet process PCR plastic-modified binder developed using each plastic source and the appropriate mixing procedure/time previously determined in this Chapter. The PCR plastic-modified binder development aimed to use as much PCR plastic as possible while maintaining the intermediate and low-temperature grade similar to the virgin binder.

A summary of the asphalt binder PG results is shown in Table 4.1. A PCR plastic dose of 1.5% was selected (for each plastic source) as this dose maintained the intermediate and low-temperature grade compared to the PG58S-28 virgin binder, with room for normal production variation. All binders would be considered to be borderline graded as their low-end continuous grade was within approximately -2°C of the -28°C threshold. The Multiple Stress Creep Recovery (MSCR) test indicated that the traffic designation of "Standard" or S was the same for all three binders. The Delta T_c values, which indicate a binder's loss of relaxation due to aging and potential increase of non-load associated cracking, passed the generally accepted criteria of warmer than -5.0°C (NCAT, 2017). Delta T_c values were close for all three binders.

Table 4.1 Asphalt binder performance grading summary

	PG58S-28 Virgin Binder	PG58S-28 + 1.5% LLDPE	PG58S +1.5% (50% HDPE + 50% LDPE)
Performance Grade	PG58-28	PG58-28	PG58-28
Continuous Grade, °C	59.0 -30.1	61.4 -29.4	61.3 -29.0
Intermediate Temp. Grade, °C	16.2	16.4	16.1
MSCR $J_{nr\ 3.2\ max}$, kPa^{-1}	3.1	2.2	2.1
MSCR Traffic Loading Designation	S	S	S
Delta T_c (ΔT_c), °C	+1.2	+1.0	+1.3

The detailed grading report for the PG58S-28 virgin binder is shown in Figure 4.9, and similar reports are shown for the PCR plastic-modified binders in Figures 4.10 and 4.11.

HSRC
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ID	PG58S-28 Flint Hills
Date Tested	12/13/2023
Tested By	AJA
Project Name	Iowa Study (For MNDOT)

DSR (Original) @ High Temps

Sample #	1	2
Temp (low) °C	58	58
G*/sinδ (kPa)	1.12	1.13
δ (degree)	87.4	87.7
Temp (high) °C	64	64
G*/sinδ (kPa)	0.520	0.530
δ (degree)	88.6	88.6

DSR (PAV) @ Intermediate Temps

Sample #	1	2
Temp (high) °C	16	16
G*·sinδ (kPa)	5,760	6,470
δ (degree)	46.7	46.7
Temp (low) °C	13	13
G*·sinδ (kPa)	8,480	9,630
δ (degree)	435.0	43.5

Viscosity

Temperature, °C	Viscosity, cP
135	261
165	79
Temperature, °C	Viscosity, Pa·s
135	0.26
165	0.08

DSR (RTFO) @ High Temps

Sample #	1	2
Temp (low) °C	58	58
G*/sinδ (kPa)	2.89	2.87
δ (degree)	84.5	84.5
Temp (high) °C	64	64
G*/sinδ (kPa)	1.3	1.26
δ (degree)	86.2	86.2

BBR (PAV) @ Low Temps

Sample #	1	2
Temp (low) °C	-24	-24
S(MPa)	478	499
m-value	0.275	0.274
Temp (high) °C	-18	-18
S(MPa)	227	237
m-value	0.330	0.331

Sample #	#1	
Continuous Grade	58.89	-30.25
Performance Grade	58S	-28

Sample #	#2	
Continuous Grade	58.97	-29.90
Performance Grade	58S	-28

Original Asphalt			Sample 1	Sample 2
Specific Gravity @ 60°F *	AASHTO T228		N/A	
Specific Gravity @ 77°F *	AASHTO T228		N/A	
Flash Point, °C *	AASHTO T48	> 230	N/A	
Viscosity, Absolute @ 140°F, Poises *	AASHTO T202		N/A	
Penetration @ 77°F, 100 g, 5 sec *	AASHTO T49		N/A	
Viscosity (Brookfield) @ 135°C Pa·s	AASHTO T316	< 3.0 Pa·s	0.26	-
Viscosity (Brookfield) @ 165°C Pa·s	AASHTO T317		0.08	-
DSR, 10 rad/sec, G*/sin δ Temp. °C, kPa	AASHTO T315	> 1.00 kPa	1.12	1.13
		Test Temp. °C	58	58
		Fail Temp. °C	58.9	59.0
RTFO Aged RAP Residue	AASHTO T240			
Mass Change, %	AASHTO T240	< 1.0% Change	-0.24	-0.25
DSR, 10 rad/sec, G*/sin δ Temp. °C, kPa	AASHTO T315	> 2.2 kPa	2.89	2.87
		Tested at	58	58
		Fail Temp. °C	60.0	59.9
MSCR	AASHTO T350	Test Temp. °C	58	58
		$J_{nr3.2\ max}$ kPa^{-1}	3.4	3.5
		$J_{nr\ Diff\ max}$, % <75%	8.5	8.5
		Traffic Loading Designation =	S	S
		$R_{0.1}$ - Average Percent Recovery at 0.100kPa =	3.2	2.9
		$R_{3.2}$ - Average Percent Recovery at 3.200kPa =	0.9	0.9
		R_{diff} - Percent Difference Between Average Recovery at 0.100kPa & 3.200kPa =	70.9	67.5
		$J_{nr0.1}$ kPa^{-1} =	3.2	3.2
PAV Aged RAP Residue	AASHTO R28			
DSR, 10 rad/sec, G*·sin δ Temp. °C, kPa	AASHTO T315	< 6000 kPa	3710	4260
	AASHTO M320 & M332	Test Temp. °C	19	19
		Pass/Fail	PASS	PASS
		6000 kPa Fail Temp. °C	15.7	16.6
BBR, Creep Stiffness and m-value,	AASHTO T313	S < 300 Mpa	227	237
60 sec @ Temp. C		m > 0.300	0.330	0.331
		Test Temp. °C	-18	-18
		Fail Temp. °C	-30.2	-29.9
		Delta Tc, °C (ΔTc = Tc,s - Tc,m) =	1.0	1.4
	CONTINUOUS GRADE		**58.9 -30.2**	**59.0 -29.9**
	PERFORMANCE GRADE		**58S -28**	**58S -28**

* From Producer
N/A Not Available

Figure 4.9 Performance Grade (PG) results for MnDOT supplied PG58S-28 virgin binder

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ID	PG58S-28 Flint Hills + 1.5% LLDPE
Date Tested	1/2/2024
Tested By	AJA
Project Name	Iowa Study (For MNDOT)

DSR (Original) @ High Temps

Sample #	1	2
Temp (low) °C	58	58
G*/sinδ (kPa)	1.55	1.52
δ (degree)	87.0	87.0
Temp (high) °C	64	64
G*/sinδ (kPa)	0.727	0.707
δ (degree)	88.0	88.1

DSR (PAV) @ Intermediate Temps

Sample #	1	2
Temp (high) °C	19	19
G*·sinδ (kPa)	4,180	4,280
δ (degree)	47.7	47.9
Temp (low) °C	16	16
G*·sinδ (kPa)	6,180	6,440
δ (degree)	44.7	44.8

Viscosity

Temperature, °C	Viscosity, cP
135	359.1675
165	117
Temperature, °C	Viscosity, Pa·s
135	0.36
165	0.12

DSR (RTFO) @ High Temps

Sample #	1	2
Temp (low) °C	58	58
G*/sinδ (kPa)	4.55	4.54
δ (degree)	83.0	83.0
Temp (high) °C	64	64
G*/sinδ (kPa)	2.03	2.03
δ (degree)	84.9	84.9

BBR (PAV) @ Low Temps

Sample #	1	2
Temp (low) °C	-24	-24
S(MPa)	544	530
m-value	0.265	0.259
Temp (high) °C	-18	-18
S(MPa)	257	248
m-value	0.323	0.325

Sample #	#1	
Continuous Grade	61.47	-29.24
Performance Grade	58S	-28

Sample #	#2	
Continuous Grade	61.28	-29.50
Performance Grade	58S	-28

			Sample 1	Sample 2
Original Asphalt				
Specific Gravity @ 60°F *	AASHTO T228		N/A	
Specific Gravity @ 77°F *	AASHTO T228		N/A	
Flash Point, °C *	AASHTO T48	> 230	N/A	
Viscosity, Absolute @ 140°F, Poises *	AASHTO T202		N/A	
Penetration @ 77°F, 100 g, 5 sec *	AASHTO T49		N/A	
Viscosity (Brookfield) @ 135°C Pa·s	AASHTO T316	< 3.0 Pa·s	0.36	-
Viscosity (Brookfield) @ 165°C Pa·s	AASHTO T317		0.12	-
DSR, 10 rad/sec, G*/sin δ Temp. °C, kPa	AASHTO T315	> 1.00 kPa	1.55	1.52
		Test Temp. °C	58	58
		Fail Temp. °C	61.5	61.3
RTFO Aged RAP Residue	AASHTO T240			
Mass Change, %	AASHTO T240	< 1.0% Change	-0.21	-0.21
DSR, 10 rad/sec, G*/sin δ Temp. °C, kPa	AASHTO T315	> 2.2 kPa	4.55	4.54
		Tested at	58	58
		Fail Temp. °C	63.4	63.4
MSCR	AASHTO T350	Test Temp. °C	58	58
		$J_{nr3.2\ max}$, kPa^{-1}	2.1	2.2
		$J_{nr\ Diff.\ max.}$, % <75%	18.8	11.8
		Traffic Loading Designation =	S	S
		$R_{0.1}$ - Average Percent Recovery at 0.100kPa =	9.5	6.9
		$R_{3.2}$ - Average Percent Recovery at 3.200kPa =	2.3	2.2
		R_{diff} - Percent Difference Between Average Recovery at 0.100kPa & 3.200kPa =	75.5	68.8
		$J_{nr0.1}$ kPa^{-1} =	1.8	1.9
PAV Aged RAP Residue	AASHTO R28			
DSR, 10 rad/sec, G*·sin δ Temp. °C, kPa	AASHTO T315	< 6000 kPa	4180	4280
	AASHTO M320 & M332	Test Temp. °C	19	19
		Pass/Fail	PASS	PASS
		6000 kPa Fail Temp. °C	16.2	16.5
BBR, Creep Stiffness and m-value,	AASHTO T313	S < 300 Mpa	257	248
60 sec @ Temp. C		m > 0.300	0.323	0.325
		Test Temp. °C	-18	-18
		Fail Temp. °C	-29.2	-29.5
	Delta Tc, °C (ΔTc = Tc,s - Tc,m) =		1.1	0.8
	CONTINUOUS GRADE		**61.5 -29.2**	**61.3 -29.5**
	PERFORMANCE GRADE		**58S -28**	**58S -28**

* From Producer
N/A Not Available

Figure 4.10 Performance Grade (PG) results for PG58S-28 binder + 1.5% LLDPE

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Highway Sustainability Research Center

ID	PG58S-28 Flint Hills + 1.5% 1.5% (50% HPDE + 50% LDPE)
Date Tested	12/26/2023
Tested By	AJA
Project Name	Iowa Study (For MNDOT)

DSR (Original) @ High Temps

Sample #	1	2
Temp (low) °C	58	58
G*/sinδ (kPa)	1.53	1.5
δ (degree)	87.1	87.1
Temp (high) °C	64	64
G*/sinδ (kPa)	0.708	0.695
δ (degree)	88.1	88.2

DSR (PAV) @ Intermediate Temps

Sample #	1	2
Temp (high) °C	19	19
G*·sinδ (kPa)	4,270	3,930
δ (degree)	47.9	44.2
Temp (low) °C	16	16
G*·sinδ (kPa)	6,440	5,720
δ (degree)	44.8	41.8

Viscosity

Temperature, °C	Viscosity, cP
135	357.5
165	115
Temperature, °C	Viscosity, Pa·s
135	0.36
165	0.12

DSR (RTFO) @ High Temps

Sample #	1	2
Temp (low) °C	58	58
G*/sinδ (kPa)	4.42	4.56
δ (degree)	83.0	83.0
Temp (high) °C	64	64
G*/sinδ (kPa)	1.98	2.04
δ (degree)	84.9	84.9

BBR (PAV) @ Low Temps

Sample #	1	2
Temp (low) °C	-24	-24
S(MPa)	541	531
m-value	0.266	0.258
Temp (high) °C	-18	-18
S(MPa)	270	263
m-value	0.326	0.322

Sample #	#1	
Continuous Grade	61.31	-28.91
Performance Grade	58S	-28

Sample #	#2	
Continuous Grade	61.16	-29.12
Performance Grade	58S	-28

Original Asphalt			Sample 1	Sample 2
Specific Gravity @ 60°F *	AASHTO T228		N/A	
Specific Gravity @ 77°F *	AASHTO T228		N/A	
Flash Point, °C *	AASHTO T48	> 230	N/A	
Viscosity, Absolute @ 140°F, Poises *	AASHTO T202		N/A	
Penetration @ 77°F, 100 g, 5 sec *	AASHTO T49		N/A	
Viscosity (Brookfield) @ 135°C Pa·s	AASHTO T316	< 3.0 Pa·s	0.36	-
Viscosity (Brookfield) @ 165°C Pa·s	AASHTO T317		0.12	-
DSR, 10 rad/sec, G*/sin δ Temp. °C, kPa	AASHTO T315	> 1.00 kPa	1.53	1.50
		Test Temp. °C	58	58
		Fail Temp. °C	61.3	61.2
RTFO Aged RAP Residue	AASHTO T240			
Mass Change, %	AASHTO T240	< 1.0% Change	-0.23	-0.23
DSR, 10 rad/sec, G*/sin δ Temp. °C, kPa	AASHTO T315	> 2.2 kPa	4.42	4.56
		Tested at	58	58
		Fail Temp. °C	63.2	63.4
MSCR	AASHTO T350	Test Temp. °C	58	58
		$J_{nr3.2\ max}$ kPa^{-1}	2.1	2.1
		$J_{nr\ Diff\ max}$, % <75%	11.0	13.9
		Traffic Loading Designation =	S	S
		$R_{0.1}$ - Average Percent Recovery at 0.100kPa =	6.5	8.7
		$R_{3.2}$ - Average Percent Recovery at 3.200kPa =	2.1	2.1
		R_{diff} - Percent Difference Between Average Recovery at 0.100kPa & 3.200kPa =	68.6	75.2
		$J_{nr0.1}$ kPa^{-1} =	1.9	1.8
PAV Aged RAP Residue	AASHTO R28			
DSR, 10 rad/sec, G*·sin δ Temp. °C, kPa	AASHTO T315	< 6000 kPa	4270	3930
	AASHTO M320 & M332	Test Temp. °C	19	19
		Pass/Fail	PASS	PASS
		6000 kPa Fail Temp. °C	16.5	15.6
BBR, Creep Stiffness and m-value, 60 sec @ Temp. C	AASHTO T313	S < 300 Mpa	270	263
		m > 0.300	0.326	0.322
		Test Temp. °C	-18	-18
		Fail Temp. °C	-28.9	-29.1
		Delta Tc, °C (ΔTc = Tc,s - Tc,m) =	1.7	0.9
		CONTINUOUS GRADE	**61.3 -28.9**	**61.2 -29.1**
		PERFORMANCE GRADE	**58S -28**	**58S -28**

* From Producer
N/A Not Available

Figure 4.11 Performance Grade (PG) results for PG58S-28 binder + 1.5% (50% HDPE + 50% LDPE)

4.4 Asphalt Binder Separation Study

The separation tendency of the PCR plastic-modified binders was evaluated in accordance with ASTM D7173 "Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt" (ASTM, 2022). This test is commonly referred to as the cigar tube test.

In this test, 50 grams of asphalt binder is poured into the cigar tube. The tube is held vertically for 48 hours at 163°C in an oven. The tube is then transferred to a -10°C freezer for 4 hours. After freezing, the tube is split into thirds and tested. The middle portion is usually discarded; only the top and bottom are tested. This test is shown in Figure 4.12.

The binder samples collected from this test were tested in the DSR in accordance with AASHTO T315 at the high PG temperature of the binders (58°C). Asphalt complex shear modulus (G*) and phase angle (δ) were measured. Any significant changes in these parameters would indicate that the plastic is separating from the binder.

Figure 4.13 shows the results of the separation test. Note that the top and bottom sections were tested for the 1.5% (50% HDPE + 50% LDPE) PCR plastic-modified binder, and all three sections were tested for the 1.5% LLDPE PCR plastic-modified binder. Testing all three sections was done to see if there was a gradient change in properties that would not be evident from testing only the top and bottom sections. Due to the increased values of asphalt complex shear modulus (G*) and phase angle (δ) noted for both specimens at the top, the data indicate that plastic may separate and float to the top. This indicates that these binders should not be stored before use but mixed and used immediately.

Figure 4.12 Separation testing (cigar tube test) of asphalt binders

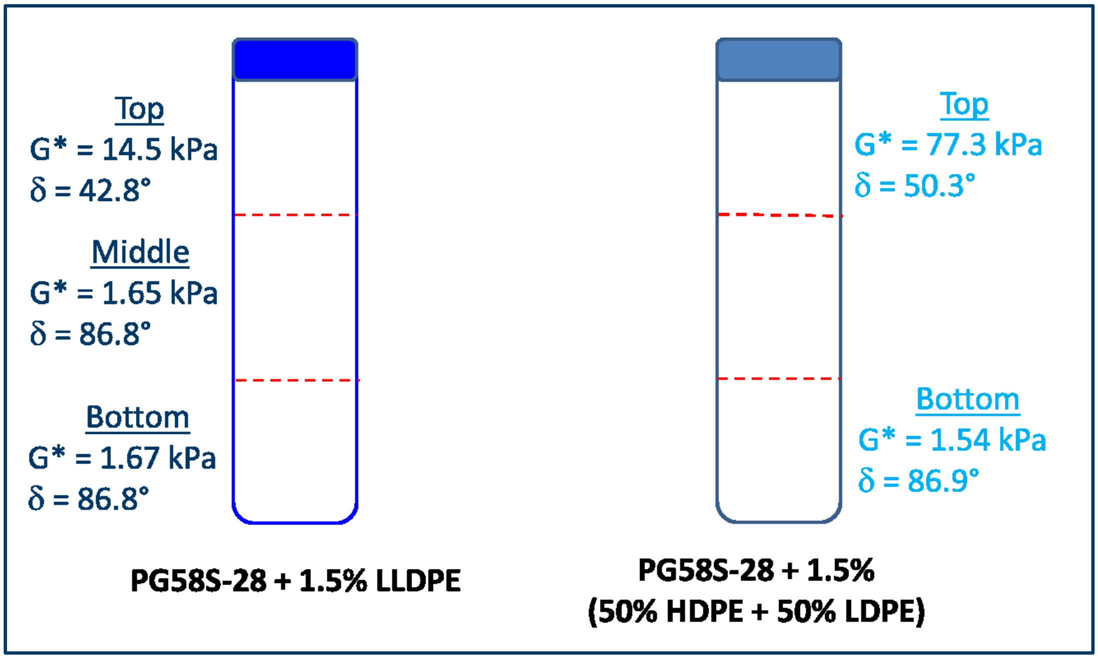

Figure 4.13 Separation testing (cigar tube test) results

4.5 MnDOT Asphalt Mixture Intermediate Temperature Cracking Performance Evaluation With & Without Plastic

The final item to be addressed for asphalt mixtures was to evaluate the effect of one of the developed PCR plastic-modified asphalt binders on a MnDOT state-approved mixture's susceptibility to intermediate temperature cracking. As outlined in the proposal, the cracking test to be used was the indirect tension asphalt cracking test (IDEAL-CT) conducted in accordance with ASTM D 8225 "Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature" (ASTM, 2022). For this cracking evaluation, the same mixture was separately prepared with the PG58S-28 virgin binder (control mix) and tested for comparison.

The plastic selected for this mixture cracking evaluation was PCR plastic source #1, LLDPE. This plastic was selected for mixture evaluation due to its low melting point. The dose of PCR plastic remained the same as the binder testing at 1.5% by weight of virgin binder. The plastic was added to the virgin binder using a wet process, which was completed immediately before mixing.

4.5.1 Mixture Mixing Procedure

The asphalt mixture design and materials utilized have been previously described in this chapter. The mixing and compaction temperatures utilized for the mixtures were determined from viscosity test results of both the virgin asphalt binder and the PCR plastic-modified binder with respect to the mixture viscosity ranges outlined in AASHTO T312 "Preparing and Determining the Density of Asphalt Mixture

Specimens using the Superpave Gyratory Compactor" (AASHTO, 2021). The determined mixing and compaction temperatures are shown in Table 4.2.

Table 4.2 Viscosity based mixing and compaction temperatures

PG58S-28 Virgin Binder	***High***	***Low***	***Average***
Mixing, ˚C	153.5	147.0	150.3
Compaction, ˚C	137.5	127.5	132.5
PG58S-28 + 1.5% LLDPE	***High***	***Low***	***Average***
Mixing, ˚C	161.0	156.0	158.5
Compaction, ˚C	149.0	141.0	145.0

The virgin aggregates were batched in the proportions shown in the mixture design and placed into an oven overnight at the respective mixing temperature. The RAP was added on top of heated aggregates 2 hours before mixing.

4.5.2 Mixture Aging, Compaction & Air Voids

After mixing, the loose mixture for each specimen was aged 4 hours at 135°C per AASHTO R30 "Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)" (AASHTO, 2021). Each loose mixture specimen was stirred every 60±5 minutes during this 4-hour aging. After aging, the loose mixture was brought to the respective compaction temperature and compacted in the Superpave Gyratory Compactor (SGC). Specimens were compacted to a height of 62 mm per the IDEAL-CT test specification. Five replicate specimens were fabricated per mixture. All specimens had compacted air voids within 7±0.5%. A visual comparison of the mixture developed with the PG58S-28 binder and with 1.5% LLDPE PCR plastic-modified binder is shown in Figure 4.14. Their visual appearance was the same.

Figure 4.14 Visual comparison of the mixtures

4.5.3 Indirect Tension Asphalt Cracking Test (Ideal-Ct) At Intermediate Temperature

Before testing, each IDEAL-CT specimen was conditioned at 25°C for at least two hours in an environmental chamber. The IDEAL-CT test is destructive. A load is applied to the specimen to obtain and maintain a constant load-line displacement (LLD) rate of 50.0 ± 2.0 mm/min throughout the test. The load and displacement (LLD) are measured, plotted and recorded. This data are then used to calculate the CT_{Index} as described in ASTM D 8225 (ASTM, 2022). Figure 4.15 shows the IDEAL-CT test device used in this study. Figure 4.16 shows an example of the load-displacement curve obtained during the test. The calculation of CT_{Index} was completed automatically by the software of the IDEAL-CT test device after each test. Generally, a higher value of CT_{Index} indicates better mixture cracking resistance at the temperature tested.

The average results of the five specimens tested for each mixture are shown in Figure 4.17. The error bars shown indicate the standard deviation of the measurements. The data indicate a reduced cracking resistance of the mixture when PCR plastic is added to the binder using a wet process compared to the same mixture with the same binder without plastic. This is consistent with the results obtained in a previous study by Abdalfattah et al. (2022).

Figure 4.15 IDEAL-CT test device

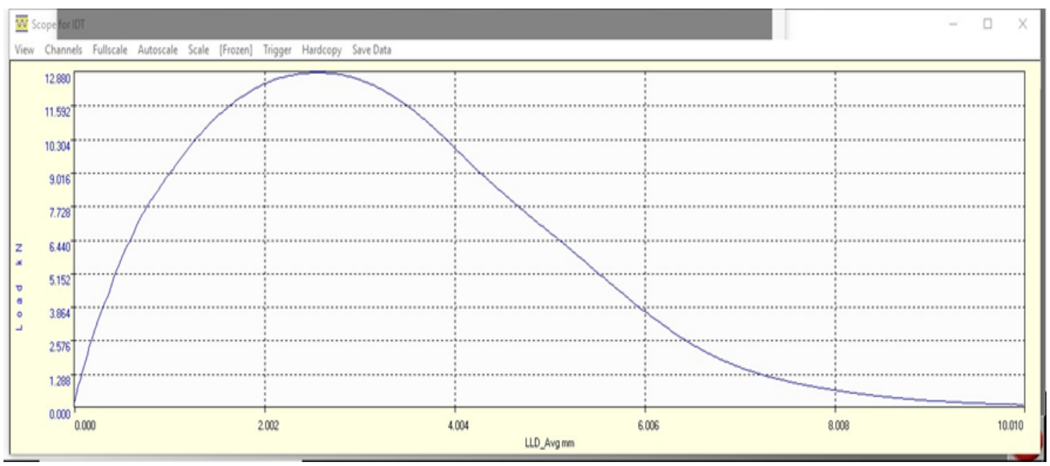

Figure 4.16 Example load-displacement curve obtained during IDEAL-CT test

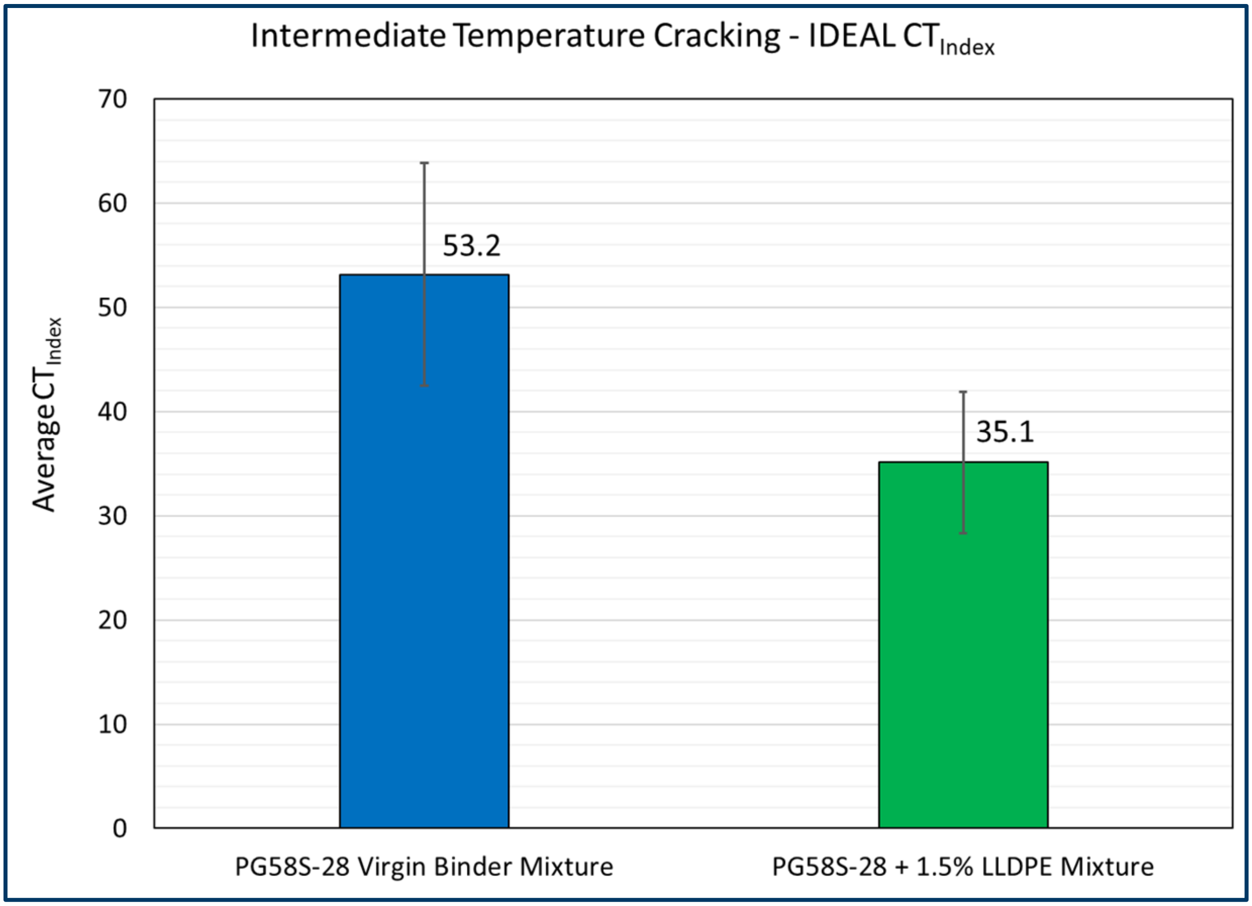

Figure 4.17 IDEAL-CT test results

4.6 Summary

The purpose of this chapter was to evaluate the incorporation of post-consumer recycled (PCR) plastics, using a wet process, into a typical MnDOT asphalt binder. For this study, MnDOT selected a PG58S-28 binder. The PCR plastic-modified binder was tested to assess the impact of PCR plastics as a binder modifier on the performance of asphalt mixtures, specifically regarding their susceptibility to intermediate-temperature cracking. A MnDOT-approved dense-graded 9.5-mm (3/8”) NMAS mixture containing 28% RAP was used in this study. Two sources of plastic were utilized, PCR plastic source #1 was LLDPE, and source #2 was a 50% mixture of HDPE and 50% LDPE. Each PCR plastic source was in pellet form and had melting points lower than a typical asphalt mixture production temperature range.

A mixing study was undertaken to determine the appropriate time to incorporate the PCR plastics into the asphalt binder using a wet process. The mixing time was determined to be when the asphalt complex shear modulus and phase angle were constant, indicating that the plastic had completely melted and blended with the asphalt binder. Fifteen minutes was determined to be the appropriate mixing time using a shear mixer. Performance grade (PG) testing was conducted on the MnDOT supplied PG58S-28 virgin binder according to AASHTO specifications. The same PG testing was conducted using the PG58S-28 virgin binder modified with each PCR plastic source. A PCR plastic dose of 1.5% by weight of virgin binder was selected (for each plastic source) as this dose maintained the intermediate and low-temperature grade compared to the PG58S-28 virgin binder.

The separation tendency of the PCR plastic-modified binders was evaluated in accordance with ASTM specifications. The cigar tube test results indicated that the plastic may be separating. This indicates that these plastic-modified binders should not be stored prior to use but should be somewhat mixed and used immediately.

The effect of one of the developed PCR plastic modified asphalt binders on the MnDOT state-approved mixture's susceptibility to intermediate temperature cracking was conducted using the indirect tension asphalt cracking test (IDEAL-CT) conducted in accordance with ASTM specifications. For this cracking evaluation, the same mixture was separately prepared with the PG58S-28 virgin binder (control mix) and tested for comparison. The plastic selected for this mixture cracking evaluation was PCR plastic source #1, which was LLDPE, and was dosed into the binder at a rate of 1.5% by the weight of the virgin binder. The test results indicated a reduced cracking resistance of the mixture when PCR plastic is added to the binder using a wet process compared to the same mixture with the same binder without plastic.

For the mixture tested, at the dose of 1.5% plastic by weight of virgin binder, approximately 0.25 tons of PCR plastic pellets would be used when paving a 12 ft wide lane, 1 inch thick, for 1 mile.

Chapter 5: Conduct Feasibility Study of Using Plastic Waste Within Concrete Roadway Paving

This chapter evaluates, through a comprehensive laboratory experimental plan, the feasibility of using plastic waste in concrete roadway paving. The study investigated the effects of incorporating various plastic materials into concrete and assessed their impact on fresh and hardened properties. The experimental program encompassed five treatment groups: an untreated PCC control group, three fiber-reinforced PCC groups with plastics, and an aggregate-replacement PCC group with plastic sand. A detailed overview of the materials, mixture proportions, and test methods used is provided. In addition, the study's results were also provided, discussing the influence of plastic addition on key parameters like workability, air content, compressive strength, tensile strength, flexural strength, and durability. This chapter aims to identify which types and concentrations of plastic materials can enhance concrete performance, thereby contributing to developing sustainable and durable concrete paving solutions. The findings offer valuable insights into the potential of plastic waste as a viable material in concrete construction, paving the way for further practical implementation.

5.1 Materials and Methods

This section offers a detailed overview of the materials used in the laboratory investigation, including properties of cement, supplementary cementitious material (SCM), aggregates, and plastic materials, along with their characteristics and gradations. It also discusses admixtures employed, such as air-entraining agents. The chapter also outlines concrete mixture proportioning, batching, and mixing procedures. Finally, it briefly introduces the different tests conducted in this study.

5.1.1 Materials

A concrete mixture consists of cement, aggregate (coarse and fine), water, and chemical admixtures. Plastic materials can be incorporated into concrete as a replacement (full or partial) for natural aggregates. All materials used in this study conformed to Minnesota standard specifications for concrete (Grade A).

5.1.1.1 Cementitious Materials

Type 1L cement was used in this study. Class C fly ash, meeting the requirements for ASTM C618, was used in this study as a supplementary cementitious material (SCM) to partially replace cement to improve its durability properties and sustainability. The chemical composition of the cementitious materials collected from the company was listed in Appendix B (Table B-1 and Table B-2).

5.1.1.2 Aggregates

Coarse aggregate of nominal maximum size 1 in and fine aggregate conforming to ASTM C33 were used. Table B-3 presents the gradation of the aggregates. The saturated surface dry (SSD) specific coarse and fine aggregate gravities were measured following ASTM C127. To determine the aggregate absorption, ASTM C128 was followed. The physical properties of the aggregates are listed in Appendix B (Table B-4).

A 50:50 (coarse: fine aggregate) ratio was chosen for this study since that combination satisfied the Tarantula curve (Ley and Cook 2014), as shown in Figure 5.1. The Tarantula curve sets the upper and limit for each sieve size (or combination of sieve sizes) to optimize the aggregate system so that the minimum cement paste requirement increases sustainability and concrete durability by maintaining the desired workability. Per ASTM C29, the measured unit weight of the combined aggregate was 126 lb/ft^3, and the volume of voids of the combined aggregate system was measured to be 24%.

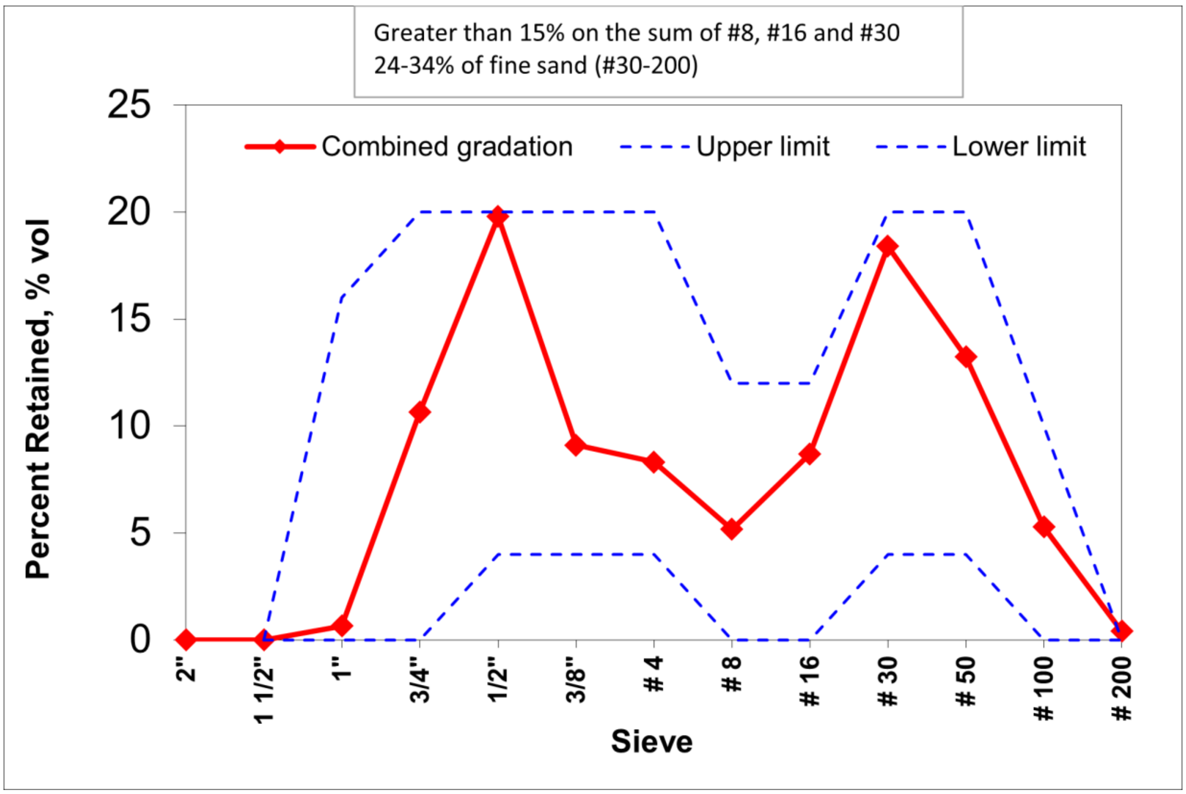

Figure 5.1 Combined aggregate gradation Tarantula curve

5.1.1.3 Plastic Materials

As shown in Figure 5.2, four types of plastic materials were tested in this study. The physical properties of the plastic materials were listed in Appendix B (Table B-4).

VIRGIN PLASTIC FIBER

The virgin plastic fiber utilized for this study was made of 100% virgin copolymer/polypropylene consisting of a twisted bundle non-fibrillating monofilament and a fibrillating network fiber. This fiber is typically used in long lengths (2-1/4") and high dosages (3.0 to 30 lbs. / cu. yd.).

RECYCLED PLASTIC FIBER-1

Recycled plastic fiber-1 was made of recycled plastic and 100% recycled polypropylene fibrillated (network) fibers. This is generally dosed between 2.5 lb. to 7.5 lb. per cubic yard of concrete.

RECYCLED PLASTIC FIBER-2

Recycled plastic fiber-2 was created by reprocessing fiber-reinforced polymer materials from retired wind turbine blades. The recommended dosage for this fiber is 5 to 10 lb/cu yard.

RECYCLED PLASTIC SAND

Recycled plastic sand is an engineered blend of recycled Polymers (proprietary blend) used as sand replacement for construction materials.

Recycled Plastic Fiber-2

Recycled Plastic Sand

Figure 5.2 Plastic materials used in this study

5.1.1.4 Chemical Admixtures

In order to ensure entrained air AIRALON 7000 air-entraining admixture (AEA) (ASTM C260) was used. Typical AIRALON 7000 admixture addition rates range from ½ to 3 fl oz/100 lbs of cement.

5.2 Mixture Proportions

The study comprised a control mixture without any plastic material, virgin plastic fiber, recycled plastic fiber-1, recycled plastic fiber-2 and recycled plastic sand mixture.

A base mixture proportion for the control mixture was determined first using the CP Tech Center (Wang et al. 2018) proportioning tool, and then for the other mixtures, aggregates were replaced with plastic material. First a suitable aggregate system was selected for the available aggregate gradation. After selecting the desired aggregate system, the cement paste quality was selected having a w/cm ratio of 0.4, fly ash comprising 30% of the total cementitious content and a target 7$\pm$1% air content.

A portion of the coarse and fine aggregate were replaced with plastic fiber (for Group-2, 3, and 4), and for Group-5, 20 vol% of the natural fine aggregate was replaced with recycled plastic sand. For all the plastic material containing mixtures, the plastic material incorporation dosage was selected based on the recommendation obtained from each respective product supplier. When developing the mixture proportion for the control, the target slump was 2 to 5 in, and target air content was 7$\pm$1%. The amount of cement paste was kept constant so that the effect of the plastic addition on the fresh properties could be compared. The detailed mixture proportions are listed in Table 5.1.

Table 5.1 Mixture proportions

Item	Control Group SSD Weights (lb./yd^3)	Virgin Plastic Fiber SSD Weights (lb./yd^3)	Recycled Plastic Fiber-1 SSD Weights (lb./yd^3)	Recycled Plastic Fiber-2 SSD Weights (lb./yd^3)	Recycled Plastic Sand SSD Weights (lb./yd^3)
w/cm	0.4	0.4	0.4	0.4	0.4
V_p/V_v (%)	200	200	200	200	200
Cementitious content	586	586	586	586	586
Cement	410	410	410	410	410
Class-C Fly Ash	176	176	176	176	176
Coarse Aggregate	1,515	1,504	1,504	1,515	1,515
Fine Aggregate	1,515	1,504	1,504	1,515	1,212
Plastic	-	7.5 vol.% of concrete	7.5 vol.% of concrete	7.5 vol.% of concrete	20 vol.% replacement of natural sand
Water	234	234	234	234	234
AEA (oz/CWT)	2	2	2	2	2

5.3 Mixing Process

Before mixing, the aggregates were collected from the barrel in buckets with proper sealing. Representative samples were taken to determine the moisture content, that was then used to adjust the weights of the aggregates and the water. For the control group without any plastic material, the following steps were followed:

- Step-1: All aggregates were placed at the drum mixer and mixed for 30 seconds.

- Step-2: The AEA was mixed with one-third of the mixture water then added to the drum mixer.
- Step-3: The ingredients were mixed for 2 minutes
- Step-4: Cementitious materials and the remaining mixture of water were added gradually
- Step-5: The ingredients were mixed for 3 minutes

Modification of the mixing process was necessary for the groups containing plastic materials. Groups with plastic fiber were mixed using the following process:

- Step-1: All the aggregates were placed at the drum mixer and mixed for 30 seconds.
- Step-2: The AEA was mixed with one-third of the mixture water then added to the drum mixer.
- Step-3: The ingredients were mixed for 2 minutes
- Step-4: Cementitious materials and one-third of the mixture water were added gradually
- Step-5: The ingredients were mixed for 3 minutes
- Step-6: Plastic fiber was added into the mixer with the remaining one-third of the mixture water
- Step-7: The ingredients were mixed for 2 minutes

The reasoning behind adding fibers at the end was to avoid fiber degradation issues. For the group with plastic sand, the following process was used:

- Step-1: All aggregates (coarse and natural fine aggregate) were placed in the drum mixer
- Step-2: The plastic sand was added, and all aggregates were mixed for 30 seconds
- Step-3: The AEA was mixed with one-third of the mixture water then added to the drum mixer.
- Step-4: The ingredients were mixed for 2 minutes
- Step-5: Cementitious materials and the remaining mixture water were added gradually
- Step-6: The ingredients were mixed for 3 minutes

5.4 Concrete Tests

- Slump test: The slump test was conducted according to ASTM C143. The target slump range was 2-5 inches.
- Air content test: The air content was measured using the pressure method in accordance with ASTM C231.
- Compressive strength test: Compressive strength tests were performed in accordance with ASTM C39 using 4 × 8-inch cylinders.
- Split Tensile strength test: The split tensile strength test was conducted in accordance with ASTM C496 using 4 × 8-inch cylinders.
- Flexural strength test: The flexural strength test was carried out in accordance with ASTM C78 using 6 × 6 × 22-inch beams.
- Electrical resistivity test: The electrical resistivity of the concrete was measured using a four-probe resistivity meter following AASHTO T358. This non-destructive test was performed on 4 × 8-inch cylinders.

5.4 Results and Discussions

This chapter presents the results of the laboratory tests and examines the impact of the addition of plastic material on both fresh and hardened concrete properties. Comparisons of performances were analyzed statistically to identify whether or not the properties of different groups significantly differed.

5.4.1 Slump Test

In this study, no water reducer was used to investigate the effect of plastic material addition on workability. With the addition of plastic material, the workability of the concrete was reduced by around 50%, as shown in Figure 5.3 and Figure 5.4. Reduced workability with plastic fiber addition, regardless of the dosage, has been reported (Gu and Ozbakkaloglu 2016) due to the increase in surface area coated with cement paste resulting in less cement paste assisting the concrete flow.

Figure 5.3 Slump-cone test (a) control (b) virgin plastic fiber (c) recycled plastic fiber-1 (d) recycled plastic fiber-2 (e) recycled plastic sand

However, for the plastic aggregate group, the angular and non-uniform or rough texture of the recycled plastic sand can be attributed to the reduced fluidity of concrete for the plastic Sand group (Figure 5.3d). Additionally, the reduced specific gravity of plastic sand compared to natural sand causes an increase in the surface area of materials to be coated with cement paste, which results in decreased workability. Previous literature also reports that partial replacement of natural fine aggregate with non-uniform plastic fine aggregate increases the yield stress of concrete (Ismail and AL-Hashmi 2008). The "yield stress" of concrete refers to the minimum stress level at which fresh concrete begins to flow. Concrete with low slump value typically refers to having higher yield stress against flow than concrete with a high slump value.

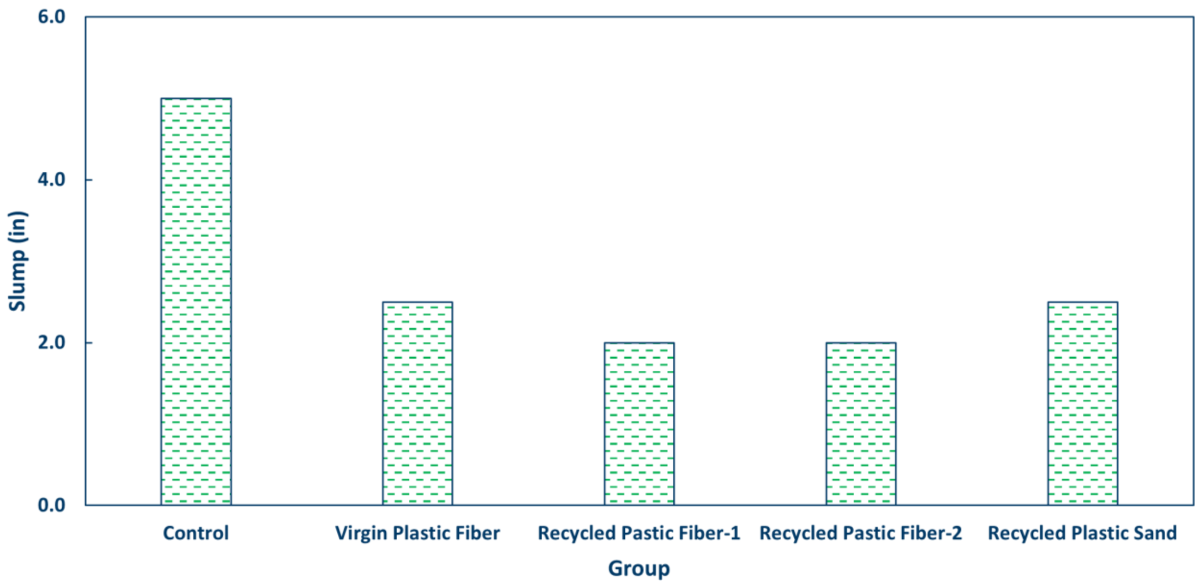

Figure 5.4 Slump-cone test results

5.4.2 Air Content

With the addition of plastic materials, the air content of the concrete decreased by approximately 30% (Figure 5.5.). There is a proportional relationship between air content and the workability of concrete: as air content increases, workability also increases, and vice versa. Typically, when concrete has the desired fluidity environment required for the efficacy of the AEA, air bubbles are formed, which also assists in lowering the yield stress of concrete. In this study, the effectiveness of AEA may have been reduced in the plastic group, where the fluidity of the concrete was hindered by the increased surface area of added plastic materials that needed to be coated with cement paste. Although based on the air content target of $7\pm1\%$, the virgin plastic fiber and recycled plastic fiber-2 mixtures failed, no measure was taken to increase the air content; the research team was interested in observing the effect of adding those plastic materials in concrete by keeping the other variables unchanged.

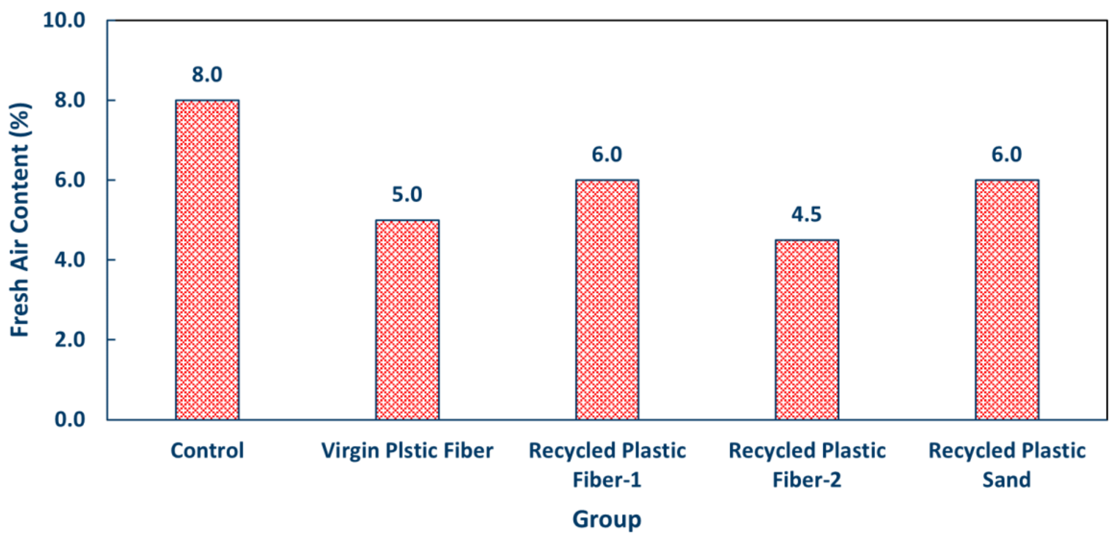

Figure 5.5 Air content test results

5.4.3 Compressive Strength

Figure 5.6 shows the 28-day compressive strength of the groups. Mixtures with higher air content typically exhibit lower compressive strength because air content directly influences the compressive strength of concrete. In this study, the increase in compressive strength was primarily observed in the plastic fiber mixtures, which might lead to the misconception that adding fibers increases compressive strength. However, the observed increase in strength was due to the reduction in air content caused by the addition of plastic fibers. The decreased air content resulted in higher compressive strength. If measures had been taken to maintain the air content in the plastic fiber mixtures at a level similar to the control mixture, the compressive strength would likely have been similar across all mixtures. The control mixture group exhibited lower strength than all fiber-reinforced mixtures.

However, despite having a lower air content than the control mixture group, the plastic sand group exhibited lower 28-day compressive strength. According to the literature, the lower elastic modulus of the plastic sands compared to natural aggregates and poor bond with cement paste generally reduces compressive strength (Gu and Ozbakkaloglu 2016). Additionally, PET plastic aggregates deteriorate when exposed to an alkaline cementitious environment (Gu and Ozbakkaloglu 2016). All these factors likely contributed to the lower 28-day compressive strength of the plastic sand group compared to the others.

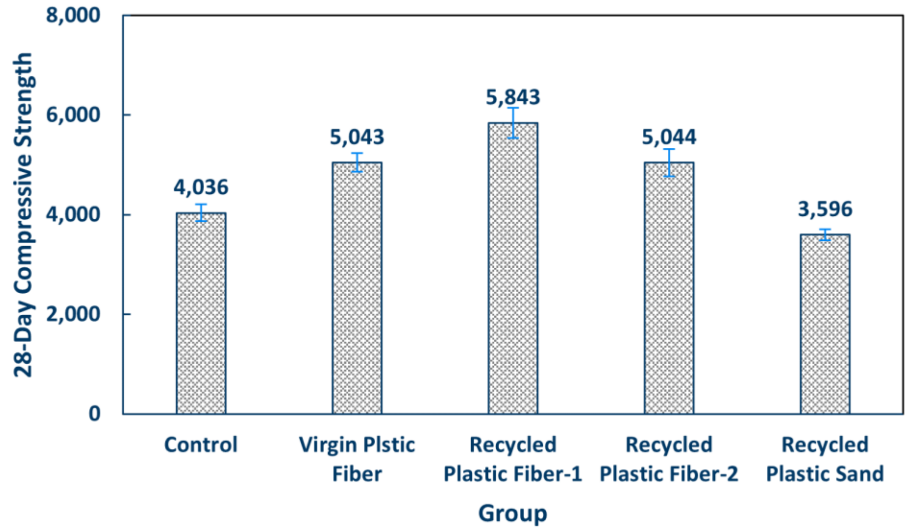

Figure 5.6. 28-day compressive strength test results

Statistical analysis was conducted to determine whether the changes in 28-day compressive strength among different groups were statistically significant. An F-test performed across all groups indicated that the null hypothesis (H_o) could be rejected (p-value < 0.0001 < 0.05) at a significance level of α = 0.95. This result suggests that at least one group's mean 28-day compressive strength was different from the others.

To further distinguish among the groups, Tukey's Honest Significant Difference (HSD) test was employed. Tukey's HSD test is a statistical technique used to identify significant differences between group means within a dataset and is commonly used as a post-hoc analysis following an ANOVA test. It helps determine whether there are significant variations between the means of different groups. Two means (μ_i and μ_j) are considered significantly different if the difference between the sample means ($\overline{y_{i.}}, \overline{y_{j.}}$) exceeds the HSD value, i.e., ($\left|\overline{y_{i.}} - \overline{y_{j.}}\right| > HSD$). The HSD value is calculated using Equation 1.

$$HSD = \frac{q_\alpha(a,N-a)}{\sqrt{2}} \sqrt{MS_{Error}(\frac{1}{n_i} + \frac{1}{n_j})} \tag{1}$$

In Equation 1, $q_\alpha(a, N-a)$ is the upper *α* percentage point of the studentized range distribution. *a* is the number of treatments or different groups, *(N-a)* is the error degree of freedom, and n_i and n_j are the number of samples in each group. If the number of samples of the groups the same ($n = n_i = n_j = \cdots$), Equation 1 can be rewritten as Equation 2.

$$HSD = q_\alpha(a, N-a)\sqrt{\frac{MS_{Error}}{n}} \tag{2}$$

Groups	Recycled Plastic Fiber-1	Recycled Plastic Fiber-2	Virgin Plastic Fiber	Control	Recycled Plastic Sand
Least Sq. Mean compressive strength (psi)	5,843	5,044	5,043	4,036	3,596

Figure 5.7 Tukey's Honest Significant Difference (HSD) analysis on 28-day compressive strength test results

Figure 5.7 shows the Tukey's Honest Significant Difference (HSD) analysis results on the 28-day compressive strength of all the groups. In Figure 5.7, groups not connected by the same color are significantly different from the others. Based on the analysis, the least square mean 28-day compressive strength of concrete with recycled plastic fiber-1 was significantly higher than the other groups. There was no statistical difference between the mean 28-day compressive strength of groups with recycled plastic fiber-2 and virgin plastic fiber. Although the recycled plastic sand group had lower 28-day compressive strength than the control group, Tukey's Honest Significant Difference (HSD) analysis suggests that the difference was not significantly different. Among all the groups, the addition of plastic sand replacing natural fine aggregate resulted in the maximum utilization of plastic materials in paving concrete. Since the 28-day compressive strength of the plastic sand group was statistically similar to that of the control group, using plastic sand may be beneficial considering the environmental benefit associated with plastic sand.

5.4.4 Split Tensile Strength

Figure 5.8 presents the 28-day split tensile strength of the groups, with the samples containing plastic materials showing improved tensile behavior compared to the control group. While enhancement in tensile behavior with the inclusion of fibers is a common phenomenon in concrete, the increase in the 28-day split tensile strength of the plastic sand group compared to the control was unexpected, so statistical analysis was conducted to determine whether this increase was significant.

The F-statistic value for the analysis of variance (ANOVA) test was 2.96, less than $F_{0.05,4,10} = 3.48$. A p-value of 0.08, greater than the significance level $\alpha = 0.05$, indicates that in this study, the null hypothesis (H_0) cannot be rejected, so it can be concluded that the mean 28-day split tensile strength of the groups is not significantly different. Since the F-test did not lead to the rejection of the null hypothesis, further analysis using Tukey's Honest Significant Difference (HSD) method was not required.

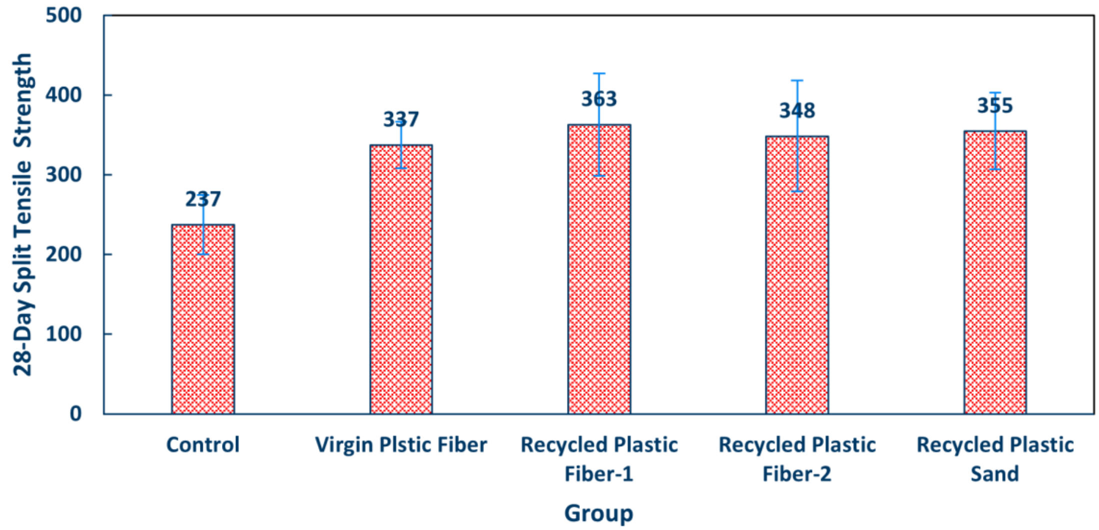

Figure 5.8 28-day split tensile strength test results

5.4.5 Flexural Strength

Figure 5.9 presents the 28-day flexural strength (modulus of rupture) of the groups. The addition of plastic fibers enhanced the flexural behavior of the concrete. As shown in Figure 5.10a, the control group samples split into two halves at the crack location upon reaching peak flexural strength. In contrast, the plastic fiber groups (Figure 5.10 b, c, and e) held tight at the peak strength and maintained integrity at peak strength due to the fiber bridging effect. Like the control group, the plastic sand sample was split into two halves at the peak flexural strength.

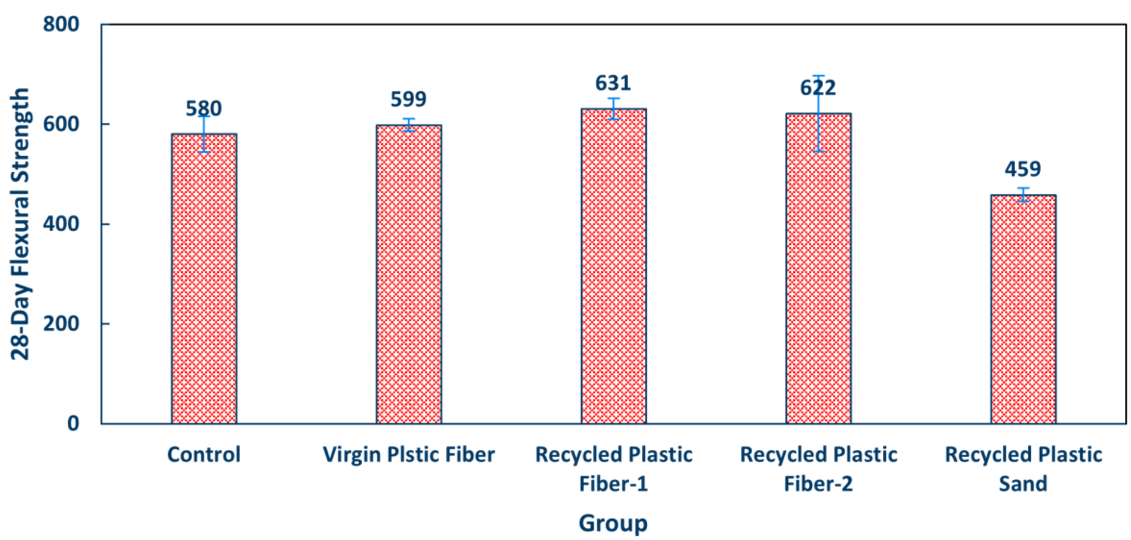

Figure 5.9 28-day flexural strength test results

In this study, the ASTM C78 test method was employed. If ASTM C1609 had been used instead, the improvement in flexural behavior due to the addition of plastic fibers would have been better demonstrated because ASTM C1609 captures residual strength readings, providing more insight into post-crack behavior. However, the research team could not perform the ASTM C1609 test for this study because of resource limitations.

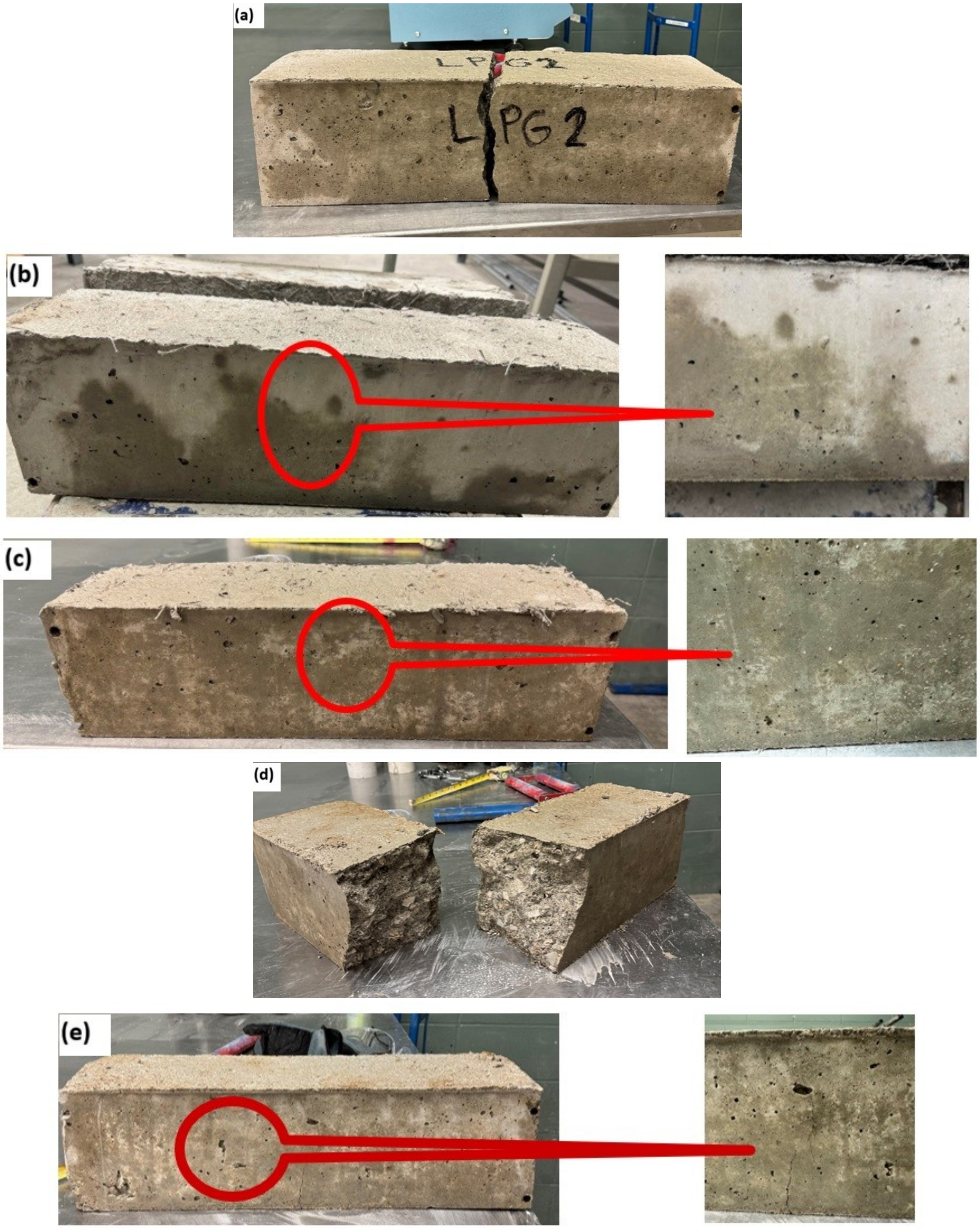

Figure 5.10 Flexural behavior of the groups (a) control (b) virgin plastic fiber (c) recycled plastic fiber-1 (d) recycled plastic fiber-2 (e) recycled plastic sand

The peak flexural strength of the plastic sand group was the lowest, primarily due to the weak bond strength between the plastic sand aggregate and the cement paste. The lower modulus of elasticity of the plastic sand also contributed to the reduced flexural strength. To determine whether this reduction in flexural strength was statistically significant, a statistical analysis was conducted. The F-statistic value from the analysis of variance (ANOVA) test was 6.26, greater than $F_{0.05,4,5}$ = 3.19. A p-value of 0.03, less than the significance level $\alpha = 0.05$, suggests that the null hypothesis (H_0) can be rejected, indicating that the mean 28-day flexural strength of at least one group was significantly different from the others. Therefore, further investigation using Tukey's Honest Significant Difference (HSD) analysis was required to identify the specific differences among the groups. According to Figure 5.11, the flexural strength of the plastic sand was not statistically significantly different than that of the control group.

Groups	Recycled Plastic Fiber-1	Recycled Plastic Fiber-2	Virgin Plastic Fiber	Control	Recycled Plastic Sand
Least sq. mean flexural strength (psi)	631	622	586	580	459

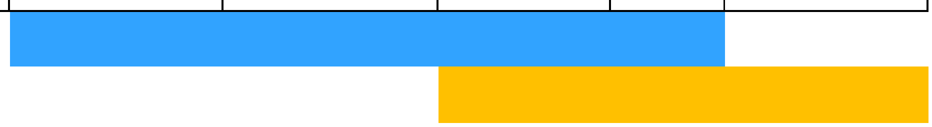

Figure 5.11 Tukey's Honest Significant Difference (HSD) analysis on 28-day flexural strength test results

5.4.6 Electrical Resistivity

The durability properties of concrete were improved by adding plastic material, as shown in Figure 5.12. Concrete's electrical resistivity depends on the pore structure: when the amount and connectivity of the pores are reduced, ion transport becomes limited. In the context of concrete durability, higher electrical resistivity means fewer or fewer interconnected pores, indicating denser and more impermeable concrete. This reduces the penetration of aggressive substances like chlorides, which can lead to reinforcement corrosion.

With increased electrical resistivity values of the plastic groups, it can be concluded that the addition of plastic improves the pore structure, and hence, the potential durability of concrete is increased. The F-statistic value from the analysis of variance (ANOVA) test was 126, greater than $F_{0.05,4,35}$ = 2.65. A lower p-value less than the significance level $\alpha = 0.05$ (p-value<0.0001<0.05), suggests that the null hypothesis (H_0) can be rejected, indicating that the mean 28-day electrical resistivity of at least one group was significantly different from the others. Therefore, further investigation was required using Tukey's Honest Significant Difference (HSD) analysis to identify the specific differences among the groups. According to Figure 5.13, the durability properties of plastic sand and recycled plastic fiber-1 were similar to each other and different from all the other groups. Compared to the control mixture, the reduced air content in the recycled plastic fiber-1 mixture likely contributed to the higher electrical resistivity due to the denser pore structure it created. Additionally, the differences in the microstructure between the plastic and natural aggregates may explain the increased electrical resistivity observed in the plastic sand mixture.

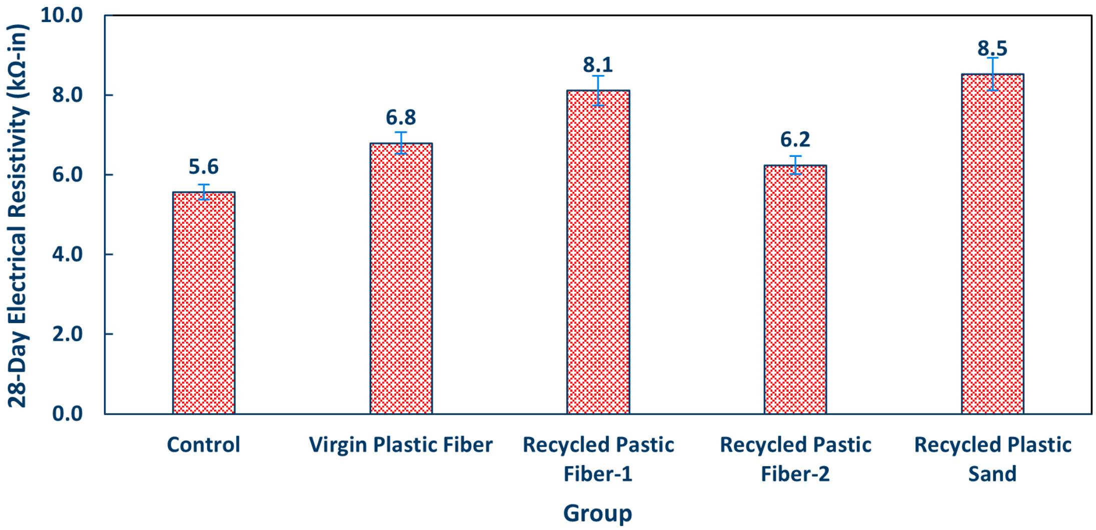

Figure 5.5.12 28-day electrical resistivity test results

Groups	Recycled Plastic Sand	Recycled Plastic Fiber-1	Virgin Plastic Fiber	Recycled Plastic Fiber-2	Control
Least sq. mean electrical resistivity $(k\Omega - in)$	8.5	8.1	6.8	6.2	5.6

Figure 5.5.13 Tukey's Honest Significant Difference (HSD) analysis on 28-day electrical resistivity test results

5.4.7 CO_2 Emission Reduction

The CO_2 emissions from typical normal-strength concrete are approximately 0.25 US tons per cubic yard (Flower and Sanjayan 2017). Based on this figure, constructing a 10-inch-thick, one-mile-long concrete pavement with a width of 12 feet results in around 500 US tons of CO_2 emissions. Without accounting for the CO_2 emissions involved in processing recycled plastic. Table 5.2 presents the approximate reduction in CO_2 emissions achieved by replacing a certain volume of concrete with recycled plastic materials. The results indicate that utilizing recycled plastic sand yields the maximum reduction in CO_2 emissions.

Table 5.2 CO_2 gas reduction by incorporating plastic material

Group	Dosage (lb./CY)	Vol.% of concrete	Per lane mile (US ton)	Approximate CO_2 emission reduction (US ton)
Virgin Plastic Fiber	7.5	0.5	9.8	2.5
Recycled Plastic Fiber-1	7.5	0.5	9.8	2.5
Recycled Plastic Fiber-2	7.5	0.2	3.9	1.0
Recycled Plastic Sand	114	6.8 (20% replacement of fine aggregates)	133	35

The calculation for the approximate CO_2 reduction in Table 5.2 is based on the vol.% replacement of concrete. For example, in the case of plastic sand, 6.8% (by volume) of concrete was replaced with plastic materials. Consequently, 6.8% of the total CO_2 emissions from 500 US tons—equivalent to 35 US tons—was excluded. However, since plastic materials are recommended as replacements for natural aggregates, evaluating the CO_2 reduction achieved specifically by replacing natural aggregates with plastic materials is more appropriate.

According to the literature (Flower and Sanjayan 2017), coarse aggregates and fine aggregates have CO_2 emission factors of 0.05 and 0.02, respectively, within a concrete mixture. Using these factors, the reduction in CO_2 emissions achieved by incorporating plastic materials as replacements for natural aggregates can be calculated, as shown in Table 5.3.

Nonetheless, the sustainability brought by the incorporation of plastic materials comes at the cost of mechanical performance, as the data from this study suggest. However, the primary advantage of using plastic materials lies in their environmental and economic benefits. Plastic waste in paving structures provides a partial solution for managing these waste materials while contributing to sustainability efforts.

Table 5.3 CO2 gas reduction by incorporating plastic material with replacement of natural aggregate

Group	Dosage (lb./CY)	Vol.% of concrete	Per lane mile (US ton)	Approximate CO_2 emission reduction (US ton)
Virgin Plastic Fiber	7.5	0.5	9.8	0.13
Recycled Plastic Fiber-1	7.5	0.5	9.8	0.13
Recycled Plastic Fiber-2	7.5	0.2	3.9	0.05
Recycled Plastic Sand	114	6.8 (20% replacement of fine aggregates)	133	2

5.5 Summary

The study conducted a laboratory investigation to evaluate the effects of incorporating plastic materials into concrete, focusing on their impact on concrete's fresh and hardened properties. The main findings are:

- Incorporating plastic materials reduced the workability and air content of concrete by approximately 50% and 30%, respectively. The reduced workability was more pronounced with the addition of plastic fibers.
- The compressive strength tests revealed that concrete mixtures containing plastic fibers had lower air content and higher compressive strength. Conversely, the recycled plastic sand group exhibited a lower compressive strength than the control, indicating that lower elastic modulus and bond of plastic sands with cement paste can influence strength development.
- The incorporation of plastic fibers led to improvements in both split tensile and flexural strength.
- The electrical resistivity tests indicated enhanced durability in concrete mixtures with plastic materials.
- The recycled plastic fiber-1 mixture exhibited higher tensile, flexural and durability properties than the other plastic fiber mixtures tested in this study.

Chapter 6: Research Benefits and Implementation Steps

Plastic waste generation has become a significant environmental challenge in the United States, necessitating sustainable solutions for its management. With increasing restrictions on plastic waste exports, cities and states are seeking innovative ways to repurpose this material. One promising approach is integrating recycled plastics into road construction, which not only addresses waste accumulation but also offers potential benefits for pavement performance. The objectives of this study were to (1) conduct a synthesis on the use of recycled plastics in roads based on a recent literature review and a developed online survey, (2) evaluate the feasibility of using plastic waste within roadway paving (asphalt and concrete), (3) recommend which applications will be most beneficial and practical, and (4) work with a technical advisory panel (TAP) from MnDOT and local road agencies to demonstrate proof–of–concept for its beneficial applications and to identify practical challenges to implementation in Minnesota's transportation infrastructure system.

6.1 Research Benefits

The proper use of plastics in road materials has the potential to offer numerous benefits, particularly enhanced durability and performance of road infrastructure. Recycled and virgin plastics can significantly improve some mechanical properties of pavement materials. These improvements could extend the service life of roads and enhance their ability to withstand environmental stresses such as temperature fluctuations, moisture, and UV exposure (Jansen et al. 2024; You et al. 2022). By addressing common performance challenges, plastic-modified road materials provide a pathway to more resilient infrastructure. From an environmental perspective, incorporating plastics in road materials promotes sustainability by addressing the global plastic-waste challenge. This approach diverts plastic waste from landfills and oceans, simultaneously reducing reliance on natural aggregates and asphalt binder, contributing to lower carbon footprints for road construction projects while supporting global recycling efforts. Integrating recycled plastics into road materials could also lead to long-term cost savings by reducing maintenance needs and material costs, creating both economic and environmental incentives. The Potential benefits of this research study include:

- Proving the feasibility of utilizing plastics in transportation and construction infrastructure.
- Reducing plastic waste in landfills and promoting resource conservation, aligning with Minnesota's environmental stewardship goals.
- Enhancing asphalt resistance to rutting.
- Lowering asphalt production costs, reducing long-term repair and maintenance expenses, and offsetting the rising demand for traditional materials.
- Providing a forward-thinking approach to sustainable infrastructure, highlighting the role of government, industry, and research institutions in advancing recycled plastic applications.

- Increasing recycling awareness and community engagement in sustainability, serving as a model for other regions seeking to implement similar solutions.
- Identifying the need for continued testing to optimize performance and material use in future road construction and rehabilitation projects.
- Enhancing tensile and flexural strength in concrete through the use of recycled plastic fibers.
- Establishing a standardized process for integrating recycled plastics into asphalt and concrete.
- Identifying challenges such as separation tendencies and reduced workability in concrete.
- Highlighting potential performance improvements with recycled plastics in asphalt and concrete mixtures.
- Providing insights into optimizing mix designs for balanced performance and sustainability.
- Addressing industry barriers, including contamination, high costs, and market limitations.
- Fostering collaboration with recycled plastic producers and suppliers for future innovation.

6.2 Implementation Steps

In this study, a series of extensive laboratory tests were conducted to assess the feasibility of incorporating recycled plastics into asphalt and concrete pavements. The outcomes of these investigations were systematically analyzed and compared, providing insights into the potential benefits and challenges, including the impact on strength, durability, and sustainability. The following implementation steps are suggested for MnDOT's use in evaluating the laboratory performance of asphalt and concrete materials incorporating recycled plastics for pavement applications.

Asphalt Pavements

- Select a suitable mixture design to study.
- Obtain necessary materials, including virgin asphalt binder, aggregates, Reclaimed Asphalt Pavement (RAP), and post-consumer recycled (PCR) plastics.
- Determine an appropriate mixing time for blending plastic into liquid asphalt using a wet process by conducting a mixing study:
- Heat the virgin asphalt binder to its mixing temperature.
- Shear mix the asphalt using a high shear mixer set to 3,000 rpm.
    - Slowly add PCR plastic pellets over a 15-minute time period.
    - Collect and test replicate binder samples at various time intervals during mixing.
    - Measure the complex shear modulus (G*) of the collected samples using a Dynamic Shear Rheometer (DSR).
    - Analyze the DSR data for all mixing times.
    - Select the optimum mixing time as the time where the complex shear modulus (G*) of the asphalt binder becomes constant.
- Perform Performance Grade (PG) testing on the PCR plastic-modified binder, at the selected dosage, to confirm the intermediate and low PG remain unchanged compared to the virgin binder.
- Conduct a separate study on the PCR plastic-modified binder using the cigar tube test to evaluate separation tendency.

- Evaluate the effect of PCR plastic-modified asphalt binder on a mixture's susceptibility to intermediate temperature cracking using the IDEAL-CT test or another MnDOT-approved intermediate temperature cracking mixture test.
  - Evaluate the mixture's susceptibility to low-temperature cracking using a MnDOT-approved mixture test.
  - Analyze all mixture data to ensure that cracking resistance of the mixture is not reduced due to the dose of PCR plastic utilized.
- Conduct a cost analysis to evaluate the financial feasibility of incorporating PCR plastic at low dosages. This analysis should consider the cost of materials, mixing processes, and potential benefits such as reduced long-term maintenance, comparing these costs with the performance improvements achieved in cracking resistance and durability.

Concrete Pavements

- Select a suitable aggregate system based on the gradation of the individual aggregates
- Select paste quantity and quality and the SSD mixture proportion of the concrete
- Select a suitable addition rate for PCR plastics
- Obtain necessary materials, including cement, fly ash, aggregates, air-entraining admixture and PCR plastics
- Immediately before the mix, determine the batch weight of aggregates and plastics based on the moisture and absorption of each of those materials
- For plastic as sand:
  - Step-1: Place all aggregates (coarse and natural fine aggregate) in the mixer
  - Step-2: Add plastic sand and mix all aggregates for 30 seconds
  - Step-3: Add AEA with one-third of the mixture water
  - Step-4: Mix for 2 minutes
  - Step-5: Add cementitious materials and the remaining mixture water
  - Step-6: Mix ingredients for 3 minutes
- For plastic as fiber:
  - Step-1: Place all aggregates (coarse and natural fine aggregate) in the mixer and mix for 30 seconds
  - Step-2: Add AEA with one-third of the mixture water
  - Step-3: Mix for 2 minutes
  - Step-4: Add cementitious materials and one-third of the mixture water
  - Step-5: Mix for 3 minutes
  - Step-6: Add plastic fiber along with the remaining one-third of mixture water
  - Step-7: Mix for 2 minutes
- Perform fresh-stage evaluation by measuring slump and air content
- Collect cylindrical and beam samples for compressive strength, split tensile strength, flexural strength, and electrical resistivity test
- At 28 days, perform compressive strength, split tensile strength, flexural strength, and electrical resistivity test

Chapter 7: Conclusions and Recommendations for Future Study

During the last decade, the use of plastic waste has become an environmental and pollution issue, creating an urgent need to explore safe and effective plastic-waste disposal methods to protect our planet and future generations. Extending the use of recycled plastic in civil engineering applications has emerged as one of the most-effective and reliable solutions for addressing the environmental and pollution issues associated with plastic waste.

Recycled plastic offers several advantages when employed in civil engineering projects. First, its use reduces dependence on virgin plastic, conserving natural resources and minimizing the energy-intensive process of plastic production. By diverting plastic waste from landfills and incineration, civil engineering applications can contribute to a circular economy, promoting a closed-loop system where materials are recycled and reused. One of the prominent uses of recycled plastic in civil engineering is in constructing roads and pavements. When processed and transformed into plastic pellets or fibers, plastic waste can be incorporated into asphalt mixes or used as a replacement for traditional aggregates in asphalt and concrete. This application enhances the durability and strength of the road infrastructure while simultaneously addressing the plastic waste crisis. Roads constructed with recycled plastic also exhibit improved resistance to cracking and weathering, resulting in reduced maintenance and repair costs. By incorporating recycled plastic into road construction, building materials, and water management systems, we can simultaneously enhance infrastructure strength and longevity while minimizing plastic's detrimental impact on our planet. Embracing these innovative approaches contributes to a sustainable future and helps safeguard future generations' well-being by protecting our environment.

The most important findings of this study are:

- This study incorporated PCR plastics into a MnDOT asphalt binder using a wet process. The selected binder was PG58S-28. Two PCR plastic sources were used, including LLDPE and a 50% HDPE/50% LDPE mixture. The appropriate mixing time was determined to be 15 minutes using a shear mixer. A PCR plastic dose of 1.5% by weight of virgin binder was selected.
- PG testing showed that the selected dose maintained the intermediate and low-temperature grade. The cigar tube test indicated a tendency for plastic separation in modified binders. PCR plastic-modified binders should be mixed and used immediately. The IDEAL-CT test showed reduced cracking resistance when PCR plastic was added. Using 1.5% PCR plastic, approximately 0.25 tons of plastic pellets would be used per mile for a 12-ft wide, 1-inch thick lane.
- Incorporating plastic materials reduced the workability and air content of concrete by approximately 50% and 30%, respectively. The reduced workability was more pronounced with the addition of plastic fibers.
- The compressive strength tests revealed that concrete mixtures containing plastic fibers had lower air content and higher compressive strength. Conversely, the recycled plastic sand group exhibited a lower compressive strength than the control, indicating lower elastic modulus and bond of plastic sands with cement paste can influence strength development.

- The incorporation of plastic fibers led to improvements in both split tensile and flexural strength. The electrical resistivity tests indicated enhanced durability in concrete mixtures with plastic materials.

7.1 Challenges

Using recycled plastics in infrastructure reduces the demand for virgin materials, potentially minimizing the environmental footprint of road construction projects. While incorporating waste plastics into infrastructure can help divert some plastic waste from landfills or incinerators, the total amount that can realistically be used remains a small fraction of the total plastic waste generated in the U.S. In addition, significant performance, engineering, and production challenges must be addressed before the full potential benefits—such as cost savings, improved infrastructure performance, and enhanced environmental sustainability—can be realized in Minnesota's transportation systems. This section identifies the challenges of fully implementing recycled plastic in Minnesota's transportation infrastructure systems. The implementation recommendations will incorporate the technical experience, knowledge gained from this project, and lessons learned from completed and ongoing studies by MnROAD/MnDOT collaborators and related research. Additionally, future research directions related to road construction using recycled plastic in Minnesota will be explored as part of a potential Phase 2 study.

7.1.1 Asphalt Pavements

According to the technical experience and knowledge gained from this project, along with lessons learned from completed and ongoing studies by MnROAD/MnDOT collaborators and related research (Al-Qadi et al., 2024; Bowers and Gu, 2021; G. Bautista et al., 2023; Giustozzi and Nizamuddin, 2022; Hasheminezhad et al., 2024; National Academies of Sciences, 2023; Tran et al., 2019), the following gaps have been identified as practical implementation challenges of using recycled plastic in Minnesota's Asphalt pavements:

- As a MnROAD ongoing study, the MnROAD HMA Reflective Cracking Challenge project (G. Bautista et al., 2023) aims to assess the field performance of hot mix asphalt (HMA) surface mixes in both new construction and reflective cracking scenarios. Test sections were constructed on MnROAD's I-94 Mainline, incorporating transverse saw-cuts in lower HMA layers to simulate overlays on pavements with existing thermal cracking. Given that most state agency asphalt projects involve overlays or mill and inlay, these test sections address a critical gap in understanding the long-term performance of HMA overlays under realistic field conditions. A key challenge in practical implementation is the need for cost-effective and durable solutions to mitigate reflective cracking, which these test sections aim to evaluate. Additionally, the collaboration between NCAT and MnROAD through the Additive Group (AG) Experiment will provide insights into the effectiveness of emerging additives, such as recycled plastics, rubber, and fibers, in improving overlay performance. Additional test sections will feature HMA mixtures with proven performance from previous studies, helping refine best practices for state agencies. Missouri's Department of Transportation and the Missouri Center for Transportation Innovation are also involved, funding related test sections in Missouri to expand the applicability of the findings.

- Developing general characterization procedures for selecting suitable waste plastics and determining the optimized dosages.
- Establishing protocols for relevant chemical and rheological testing of waste plastic modified binders.
- The NCAT literature review (Bowers and Gu, 2021; Tran et al., 2019) identified around 200 field projects using recycled plastics in asphalt pavements, most of which were constructed with Novophalt between the late 1980s and early 2000s. However, their field performance data are poorly documented. Limited available data suggest that Novophalt pavements performed well in terms of rutting resistance, although one study noted reduced cracking performance compared to pavements with unmodified or SBS-modified binders (Bowers and Gu, 2021) . In recent years, several demonstration projects involving recycled plastic-modified asphalt have been constructed in various countries, including Australia, Canada, and the U.S. While these projects have shown promising early performance, their long-term durability is still uncertain due to their relatively recent construction.
- A complete life-cycle assessment (LCA) is needed that includes use of alternative plastics and quantifies the environmental impacts.
- Understanding the potential generation of microplastics and leaching issues of waste plastic-modified asphalt.
- Large-scale testing is necessary to evaluate the environmental impact, biodegradability, and sustainability of modified asphalt with recycled plastic, particularly regarding their long-term behavior. However, such testing should be conducted only after smaller-scale efforts have shown promising results, ensuring that the material's performance and potential benefits are sufficiently validated at a preliminary level.
- Studies have consistently shown that adding recycled plastics stiffens asphalt binders and mixtures, improving high-temperature shear resistance and enhancing rutting performance. However, this stiffening effect can negatively impact fatigue and thermal cracking resistance due to increased embrittlement and reduced relaxation properties. In countries like the U.S., where cracking is the primary distress affecting asphalt pavement lifespan, future research on recycled plastic-modified (RPM) asphalt should focus more on cracking resistance, considering the effects of asphalt aging.
- Another concern is the applicability of current laboratory tests for wet-process RPM binders. The Superpave Performance-graded (PG) test methods and other rheological and chemical tests assume asphalt binders are homogeneous, but this assumption may not hold for RPM binders due to phase separation tendencies. This may necessitate modifications to test methods. In addition, certain recycled plastics are insoluble in the solvents used for asphalt extraction and analysis, complicating the characterization of RPM asphalt binders.
- RPM asphalt mixtures also show potential for high-modulus asphalt concrete applications, which could reduce pavement thickness in design. However, this benefit has not been systematically

quantified and requires further investigation through testing, design analysis, and field evaluations.

- There is also a need to understand the dry process of adding recycled plastics to asphalt better. Key questions include the role of plastics in the mixture, how they affect volumetric mix design, and whether they influence surface texture, skid resistance, and rolling resistance. These areas require further exploration to optimize the use of recycled plastics in asphalt pavements.
- Long-term performance monitoring of both new and existing field projects using RPM asphalt mixtures is essential for collecting data to quantify the impact of recycled plastics on the service life of asphalt pavements. This data are critical for life-cycle cost analysis and life-cycle assessment of RPM mixtures. A global pavement performance database incorporating projects of different ages, road classifications, traffic levels, climate conditions, and pavement structures would be highly beneficial. To ensure consistency, this data should be collected and analyzed in line with standards set by federal or state highway agencies.

The following challenges in using RPM in asphalt materials have been identified:

- Difficulty characterizing a wide variety of plastics, particularly those within the same category, in instances where plastics fail rheological tests but show good asphalt mix performance tests.
- Challenges in solvent extraction and recovery of waste plastic-modified asphalt binder due to differences in solvency of the materials.
- Existing studies agree that producing a homogeneous and storage-stable RPM asphalt binder is challenging due to its tendency for phase separation. To address this, researchers have tried adding stabilizing agents or compatibilizers and chemically modifying the recycled plastics to enhance compatibility with asphalt. While some laboratory formulations have shown promising results, further research is needed to explore a wider variety of recycled plastics with diverse sources and properties and different types of asphalt binders to understand their interactions and performance fully.
- Many studies have evaluated the effects of adding recycled plastics to asphalt mixtures using both the wet and dry processes. Most used the Marshall stability test and found that recycled plastics increased the Marshall stability and stability index (or quotient), which some researchers interpreted as an indication of better rutting resistance and potentially longer pavement life. However, this interpretation is flawed, as the Marshall stability test does not correlate well with field rutting performance (Giustozzi and Nizamuddin, 2022) . Additionally, the service life of asphalt pavements depends heavily on cracking performance, so improving rutting alone with recycled plastics does not guarantee better field performance or a longer pavement lifespan.
- Significant safety and operational concerns exist regarding how recycled plastics can be introduced into asphalt plants for the dry process. Introducing plastics via the cold feed conveyor is unsafe, as they could reach their flash point and ignite on contact with the burner flame, potentially causing explosions. Instead, adding plastics through the RAP conveyor or at the RAP entry port is safer. Another safety issue is that fine plastic particles might coat and blind the filter bags in the baghouse, compromising its efficiency and increasing the risk of a fire.

- There is a lack of knowledge on how highway agencies can conduct quality-assurance testing to verify the amount and properties of recycled plastics during asphalt production. Similarly, asphalt contractors need guidance on process control and quality control testing before and during production to ensure the consistency and quality of RPM asphalt mixtures.
- In terms of construction, demonstration projects are necessary to assess any potential changes in construction practices for RPM asphalt mixtures. Due to increased binder viscosity and mix stiffness, RPM mixtures may be less workable and harder to compact, making it challenging to achieve proper in-place density. Warm mix asphalt (WMA) technologies could help with compaction, provided there is no compatibility issue between WMA additives and recycled plastics, but no data are currently available on this interaction.
- There are also significant knowledge gaps related to health, safety, and environmental impacts. Occupational exposure to hazardous air pollutants and potential per- and polyfluoroalkyl substances (PFAS)s from heating recycled plastics, especially post-consumer recycled (PCR) plastics, is a major concern during production and construction. Additionally, the impact of recycled plastics on the recyclability of asphalt, particularly with the dry process, remains unclear. Environmental concerns include the potential release of microplastics and nano-plastics from the weathering and milling of RPM pavements and the leaching of harmful substances like phthalates. These issues require further investigation to ensure the safe and sustainable use of recycled plastics in asphalt.
- According to Giustozzi and Nizamuddin (2022), previous studies have shown that adding recycled plastics to asphalt mixtures improves stiffness and rutting resistance. In the wet process, this improvement is due to the stiffening effect on the asphalt binder. In the dry process, the enhanced stiffness and rutting resistance are attributed to increased internal friction within the aggregate structure, improved aggregate quality from plastic-coated aggregates, and binder stiffening due to plastic modification. Research in India suggests that recycled plastics melt in the dry process, forming a thin plastic coating on aggregates, which improves toughness, abrasion resistance, and bond strength and reduces asphalt absorption, leading to better overall performance. However, only a few studies have explored the impact of recycled plastics on cracking and moisture resistance, with outdated methods and inconsistent results.

7.1.2 Concrete Pavements

According to the technical experience and knowledge gained from this project, along with lessons learned from completed and ongoing studies by MnROAD/MnDOT collaborators and related research (Hasheminezhad et al., 2024; Minde et al., 2024; National Academies of Sciences, 2023; Oddo et al., 2024) , the research team identified several challenges in the practical implementation of plastic waste in Minnesota’s concrete pavements.

7.1.2.1 Reduced Workability and Air Content

One of the key issues identified in the study is the reduced workability of concrete mixtures containing plastic fibers or sand. Plastic materials, particularly fibers, increase the surface area that needs to be coated with cement paste, decreasing the concrete's fluidity. This can make it more difficult to handle and place during construction. However, this challenge can be eliminated by using water reducers, which were intentionally avoided in the current study.

Maintaining the proper air content in concrete is critical for withstanding Minnesota's freeze-thaw cycles. The addition of plastic materials can reduce air content by up to 30%, as observed in the study. The entrained air in concrete helps absorb stress from freezing and thawing, and a reduction in air content could compromise the durability of plastic-modified concrete in cold environments. However, this challenge can be avoided by modifying the fluidity of the mixture with the usage of necessary admixtures so that the air-entraining admixture can become functionally more effective.

Further research is required to learn about recycled plastics' long-term physical and chemical interaction with other concrete admixtures, such as water reducers and air-entraining admixtures.

7.1.2.2 Bonding Issues

Plastic sand exhibited weaker bonding characteristics with the cement matrix than natural aggregates. This weaker Interfacial Transition Zone (ITZ) can reduce the concrete's overall strength. Furthermore, plastic sands have a lower elastic modulus, which diminishes their ability to provide adequate load transfer across the pavement. This issue could lead to early failures in high-traffic areas, raising concerns about the long-term performance of concrete containing plastic sand. However, concluding without analyzing field performance from test sites constructed with the product would be unreasonable. Field testing is essential to accurately assess plastic sand-containing concrete's practical performance and long-term durability.

7.1.2.3 Logistic Barriers

Although the long-term benefits of using recycled plastics in concrete can be significant, it also presents several economic challenges. Processing plastic waste—through collection, sorting, cleaning, and preparing it for concrete applications—can be cost-intensive, and these expenses must be weighed against potential savings. Furthermore, the logistics of collecting, processing, and integrating plastics into concrete production can be complex, requiring collaboration between recycling facilities and construction companies. Establishing a streamlined supply chain for plastic materials could take considerable effort and investment.

7.1.2.4 Environmental Considerations

The long-term performance of concrete containing plastic requires further investigation, considering the susceptibility of plastic materials to weathering and degradation from environmental factors like sunlight, heat, and freeze-thaw cycles, which can weaken the plastic over time and potentially impact the durability of the concrete. In addition, the interactions between certain plastics and the cement matrix over extended periods are not fully understood, raising concerns about potential chemical reactions that could affect concrete properties and lead to unforeseen consequences. Moreover, the lack of long-term data on the performance of plastic-containing concrete in real-world applications makes it difficult to assess its suitability for various construction projects and predict its long-term behavior.

A comprehensive LCA is essential to understand the environmental impact fully. Key factors requiring careful evaluation include energy consumption, as processing plastic waste into forms suitable for concrete demands energy. In addition, the carbon footprint across the entire life cycle—encompassing processing, transportation, and potential end-of-life scenarios—must be assessed to determine the overall environmental impact. Furthermore, there is a risk of unintended environmental consequences, such as the potential release of microplastics from concrete over time or impacts related to the processing and disposal of plastic waste, all of which require thorough investigation.

7.1.2.5 Lack of Specifications

A lack of widely accepted standardization and regulations governing plastic waste in concrete poses significant challenges to its widespread adoption. Without established guidelines, there can be inconsistencies in plastic-modified concrete quality, safety, and performance, making it difficult for engineers and contractors to integrate these materials into large-scale projects confidently.

Regulatory agencies may hesitate to approve plastic waste in critical infrastructure without reliable data and standardized benchmarks that guarantee long-term performance, particularly in high-stress environments like roads and bridges. Concerns about the potential variability in the source and composition of recycled plastics also make it difficult to ensure uniform performance across different batches of plastic-modified concrete.

Establishing clear guidelines and regulations is essential to ensure plastic waste is processed and incorporated into concrete safely and effectively. This would include setting specific criteria for plastic types, quality standards for plastic materials, and stringent testing procedures to ensure the modified concrete meets or exceeds traditional performance standards. Collaboration between regulatory bodies, research institutions, and industry stakeholders will be crucial in developing these standards and fostering greater confidence in the use of plastic waste in concrete.

7.2 Recommendations for Future Studies

The following recommendations are suggested for asphalt pavements:

- Develop protocols to ensure compatibility and blending of waste plastics with binders.
- Perform benefit-cost evaluations, conduct life-cycle assessments, and comprehend the impact of incorporating recycled plastics in asphalt pavements.
- Large-scale evaluation and demonstration of using recycled plastic in asphalt pavements are needed. However, such testing should be conducted only after smaller-scale efforts have shown promising results, ensuring that the material's performance and potential benefits are sufficiently validated at a preliminary level.

The following recommendations are suggested for concrete pavements:

- The long-term performance and durability of plastic-containing concrete remain uncertain, influenced by environmental factors like weathering, which could weaken the materials over time, and potential chemical interactions that are not fully understood.
- Although using plastic waste can reduce reliance on virgin aggregates and promote waste diversion, it involves substantial processing costs and presents economic challenges, including the risk of higher maintenance expenses due to uncertain long-term performance. Additionally, a comprehensive life-cycle assessment is essential to evaluate the environmental impact, including energy consumption, carbon footprint, and potential risks like microplastic leakage, all of which require thorough investigation.
- Future research involving wind turbine blades as a source of plastic material for concrete presents a promising avenue. Wind turbine blades, composed of fiber-reinforced polymers, offer unique structural benefits when repurposed into concrete reinforcement fibers. Future studies should explore the long-term performance of concrete containing wind turbine blade fibers, particularly in freeze-thaw conditions like those in Minnesota. Moreover, research should examine the environmental impact, such as the potential for microplastic release, and conduct a comprehensive LCA to assess the sustainability benefits. Field trials and test sections using wind turbine blade fibers in concrete would also be valuable to verify laboratory findings and assess the material's real-world applicability.

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Appendix A: Questionnaires

Questionnaire for MN-DOT, Plastic for Paving (Part 1)

This survey is being conducted as part of the Minnesota Department of Transportation (MnDOT) and Minnesota Local Road Research Board (LRRB) sponsored research project entitled **Use of Plastics in Road Materials (Paving)**.

The objective of this survey is to collect information about material recovery facilities across Minnesota and recycled-plastic suppliers across the U.S. The survey should take approximately 10 minutes to complete. We appreciate your time and assistance in successful completion of the research project.

Benefit of Participation:

This survey is being conducted throughout Minnesota and elsewhere, and the results of this survey will be shared with participants upon request. After completion of the research project, we will provide you with an electronic copy of the project final report.

Please provide the following information

Company: ___________
County: ___________
Name: ___________
Email: ___________
Phone: ___________

If you use the MS Word version of the survey, please email the survey to Araz Hasheminezhad, or Dr. Halil Ceylan at the following email addresses:

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1. How would you categorize your facility based on the choices below?
   a. Material-recovery facility (MRF) - recover recyclable materials from municipal solid wastes ☐
   b. Recycled-plastic supplier (RPS) - reprocess pre-treated plastic from MRF to recycled plastic products ☐
   c. Both ☐

If your facility is an MRF, please answer Questions 2 through 4.
If your facility is an RPS, please answer Questions 5 through 8.
If your facility is a combination MRF and RPS, please answer all questions.
If your facility would be categorized as something else, please specify:
____.

Questions (Q2 – Q4) are for material recovery facilities (MRF):

2. What percentage of collected plastic at your facility is consumer plastic waste?
   a. < 40% ☐
   b. 40 - 60% ☐
   c. 60 - 80% ☐
   d. > 80% ☐
   e. No available record ☐
3. What are the sources of waste plastics you collect at your facility? Mark all that apply.
   a. Municipal solid waste (MSW) or consumer waste plastics ☐
   b. Commercial and industrial (C&I) waste plastics ☐
   c. Construction and demolition (C&D) waste plastics (PVC pipes, plastic blocks, plastic roof panels, plastic wall panels, etc.) ☐
   d. No available record ☐
4. What types of plastic waste do your facility recycle? Mark all that apply.
   a. Type I: Polyethylene terephthalate (PET or PETE) ☐
   b. Type II: High-density polyethylene (HDPE) ☐
   c. Type III: Low-density polyethylene (LDPE) ☐
   d. Type IV: Vinyl/Polyvinyl chloride (V or PVC) ☐
   e. Type V: Polypropylene (PP) ☐
   f. Type VI: Polystyrene (PS) ☐
   g. Type VII: Other (resins, acrylonitrile butadiene styrene, nylon, etc.) ☐
   h. No available record ☐

Questions (Q5 – Q8) are for recycled plastic suppliers (RPS):

5. What kind of recycled plastic products does your facility/company produce and provide? Mark all that apply.

Types of Outputs	Shape
PET or PETE (Type I) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________
HDPE (Type II) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________
LDPE (Type III) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________
V or PVC (Type IV) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________
PP (Type V) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________
PS (Type VI) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________
Other types (Type VII) ☐	Strip ☐ Pellet ☐ Granule ☐ Flake ☐ Other__________

6. Can your facility/company customize the size and shape of recycled plastic products?

   a. Yes ☐
   b. No ☐

7. What are typical applications of the recycled plastic products produced from your facility/company? For example, recycled PET pellets from some facilities/ companies can be used to produce food-grade containers. Mark all that apply.

Types of Outputs	Applications of Recycled Plastic Products
PET or PETE (Type I) ☐	
HDPE (Type II) ☐	
LDPE (Type III) ☐	
V or PVC (Type IV) ☐	
PP (Type V) ☐	
PS (Type VI) ☐	
Other types (Type VII) ☐	

8. Is the recycled plastic you produce at your facility 100% recycled plastic, or do you use a certain percentage of virgin plastic material in the production step? If yes, can you identify the percentage of recycled plastic in the finished product of your facility?
   a. Yes. It contains _________% recycled plastic ☐
   b. No or No available record ☐

We are exploring options to conduct virtual interviews for more information our research objectives. Please indicate your interest in participating in an interview through a virtual meeting platform.

Yes, I am interested in participating in a virtual interview. ☐

No, I am not interested in participating in a virtual interview. ☐

Any comments you would like to share with us?

____

Questionnaire for MN-DOT, Plastic for Paving- Part 2

This survey is being conducted as part of a Minnesota Department of Transportation (MnDOT) and Minnesota Local Road Research Board (LRRB)-sponsored research project entitled **Use of Plastics in Road Materials (Paving)**.

The objective of this survey is to collect information about material recovery facilities across Minnesota and recycled plastic suppliers across the U.S. The survey should take approximately 10 minutes to complete. We appreciate your time and assistance in the successful completion of the research project.

Benefit of Participation:

This survey is being conducted throughout Minnesota and elsewhere, and the results of this survey will be shared with the participants upon request. After completion of the research project, we will provide you with an electronic copy of the project final report.

Please provide the following information

Company: ___________
County: ___________
Name: ___________
Email: ___________
Phone: ___________

If you use the MS Word version of the survey, please email the survey to Araz Hasheminezhad or Dr. Halil Ceylan at the following email addresses:

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1. How would you categorize your facility based on the choices below?
    a. Material-recovery facility (MRF) - recover recyclable materials from municipal solid wastes ☐
    b. Recycled-plastic supplier (RPS) - reprocess pre-treated plastic from MRF to recycled plastic products ☐
    c. Both ☐

If your facility is an MRF, please answer Questions 2 through 5 and 9.
If your facility is an RPS, please answer Questions 6 through 9.
If your facility is a combination MRF and RPS, please answer all questions.
If your facility would be categorized as something else, please specify:

____

Questions (Q2 – Q5) are for material recovery facilities (MRF):

2. What quantity of plastic waste is collected annually at your facility?
    a. < 20,000 US tons ☐
    b. 20,000 – 40,000 US tons ☐
    c. 40,000 – 60,000 US tons ☐
    d. > 60,000 US tons ☐
3. What types of plastic waste does your facility recycle? Mark all that apply.
    a. Type I: Polyethylene terephthalate (PET or PETE)☐
    b. Type II: High-density polyethylene (HDPE) ☐
    c. Type III: Low-density polyethylene (LDPE) ☐
    d. Type IV: Vinyl/Polyvinyl chloride (V or PVC) ☐
    e. Type V: Polypropylene (PP) ☐
    f. Type VI: Polystyrene (PS) ☐
    g. Type VII: Other (resins, acrylonitrile butadiene styrene, nylon, etc.) ☐

4. Please indicate the disposal method and capacity for different plastic types (types refer to Q3).

Disposal Method	Plastic Types	Annual Disposal Capacity (US tons)
Send to reprocess and produce recycled plastic products		
Send to landfills		
Send to waste-to-energy facilities for combustion		
Send to incinerators		
Other, please specify: ____________________________		

5. What are the procedures for waste-plastic processing in your facility? Mark all that apply.
   a. Collect waste plastic from the local curbside/community recycling bins ☐
   b. Sort waste plastics by plastic types identified in Q3 and remove all contaminants (e.g., liquid in containers, residual foods, paper, glass, and metal) ☐
   c. Send sorted plastics to another facility for reprocessing and producing recycled plastic goods ☐
   d. Send sorted plastics to landfills ☐
   e. Send sorted plastics to waste-to-energy facilities for combustion ☐
   f. Send sorted plastic to incinerators ☐
   g. Other, please specify____________________________________ ☐

Questions (Q6 – Q8) are for recycled plastic suppliers (RPS):

6. What quantities of pre-treated plastic does your facility collect from a material-recovery facility (MRF) for reprocessing and producing recycled plastic products? Mark all that apply.

Types of Inputs	Annual Collection Amount (US ton)
PET or PETE (Type I) ☐	
HDPE (Type II) ☐	
LDPE (Type III) ☐	
V or PVC (Type IV) ☐	
PP (Type V) ☐	
PS (Type VI) ☐	
Other types (Type VII) ☐	

7. What are the typical amounts of recycled plastic products your facility produces every year? Mark all that apply.

Types of Outputs	Annual Output (US ton)
PET or PETE (Type I) ☐	
HDPE (Type II) ☐	
LDPE (Type III) ☐	
V or PVC (Type IV ☐	
PP (Type V) ☐	
PS (Type VI) ☐	
Other types (Type VII) ☐	

8. Does your facility employ quality control/quality assurance (QC/QA) tools (specifications of raw materials and finished products, documentation of plant, equipment and process, standardized sampling plans and laboratory testing, etc.) to control/assure the quality of recycled plastic products during manufacturing?
   a. Yes ☐
   b. No ☐

Question 9 is for both material recovery facilities (MRF) and recycled plastic suppliers (RPS):

9. What limitations and/or challenges related to plastic-waste recycling and reuse you might have been / may be experiencing? Mark all that apply.
   a. Contaminations in collected plastics such as residual food and liquid ☐
   b. Technical difficulties to recycle and reprocess plastics ☐
   c. Quality control/quality assurance (QC/QA) during reprocessing plastics ☐
   d. High cost of recycling and/or reprocessing plastics ☐
   e. Limited market size and not enough clients ☐
   f. Lack of policy support at the national and state levels ☐
   g. Others, please specify:__________________ ☐

Any comments you would like to share with us?

Appendix B: Material Properties

Table B.1 Composition/information on 1L cement ingredients

Materials	%
Cement, Portland, chemicals	77-95
Gypsum ($Ca(SO_4).2H_2O$)	4 – 8
Magnesium oxide (MgO)	0.5 – 7
Limestone	0 – 15
Calcium oxide	≤ 3.5
Flue dust, Portland Cement	≤ 2.75
Quartz	0.02 – 0.21
Nickel	0.001 – 0.013
Chromium, ion (Cr 6+)	0 – 0.012

Table B.2 Composition/information on Fly Ash

Chemical Analysis	%	Physical Analysis	%
SiO_2	39.38	Amount retained on No. 325 Sieve	17.5
Al_2O_3	19.63	Strength Activity Index	
Fe_2O_3	6.24	Portland cement @ 7 days, % of control	95
CaO	22.96	Portland cement @ 28 days, % of control	97
MgO	5.03	Water requirement, % of control	93
Na_2O	1.39	Autoclave expansion, %	+0.02
K_2O	0.59	Density	2.67
SO_3	1.07		
Moisture Content	0.05		
Loss on Ignition	0.29		
Total Alkalis, % as Na_2O Equivalent	1.78		
Available Alkalis, % as Na_2O Equivalent	0.75		

Table B.3 Gradation of coarse and fine aggregates

Sieve	% Pass (Coarse)	% Pass (Fine)
2”	100.0	100.0
1.5”	100.0	100.0
1”	98.7	100.0
¾”	77.3	100.0
½”	37.5	100.0
3/8”	19.2	100.0
#4	4.2	98.3
#8	2.4	89.8
#16	1.7	73.2
#30	1.3	37.0
#50	1.0	11.0
#100	0.8	0.7
#200	0.5	0.2
<200	0.0	0.1

Table B.4 Physical properties of aggregates and plastic materials

Materials	Specific Gravity	Absorption (%)
Coarse aggregate	2.68	0.16
Fine aggregate	2.65	3.18
Forta-Ferro	0.91	0.86
Forta-Green	0.91	1.72
NVI Sand	1.00	0.83
Regen Fiber	2.40	0.83