Plastic Waste In Road Construction: A Path Worth Paving?

Application of Dry Process in South Asia

Pawan Patil • Natalya Stankevich • Nina Tsydenova • Zoie Diana

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This report is part of a larger series of stocktaking and analytical products on plastic pollution in South Asia. This work is undertaken as part of the World Bank's work program on South Asia Marine Plastics Pollution, which aims to promote circular plastic economy solutions, advance related country-level policy and investment dialogues, and raise awareness of the deleterious impacts of marine plastics pollution on people's lives and livelihoods. It supports the Bank's commitment to work with countries of South Asia to pursue and scale-up policies and programs that help them move toward a circular plastic economy and, in partnership with civil society and the private sector, harnesses the power of innovation to bring viable and sustainable solutions for plastic waste reduction and management across the region.

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Plastic pollution is a widespread and pressing environmental crisis in South Asia. Although we need to turn off the tap on plastic pollution, we must find ways to deal with the existing mountains of plastic waste, much of which is not recyclable. Meanwhile, some roads may be a potential application of this plastic waste as discussed in this new report, but much more research needs to be conducted moving forward to ensure any negative externalities are properly understood and addressed.

Christophe Crepin, Practice Manager, South Asia Environment,
Natural Resources and the Blue Economy

Roads, and particularly rural roads, are essential for connectivity, economic development, and poverty reduction across South Asia. One of our objectives is to support our clients in building roads and other infrastructure more sustainably. This report is another important step on the pathway toward understanding the sustainable development of connectivity with roads.

Shomik Raj Mehndiratta, Practice Manager, South Asia Transport

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Our new report, Plastic Waste in Road Construction: A Path Worth Paving? provides a first close examination of the technology and process that enables the use of difficult to recycle plastic waste material in road construction. With thousands of kilometers of so called "plastic roads" slated for construction across the world, including South Asia, it's a good time to put a spotlight on the technology and kick-start a discussion on its pros and cons.

John Roome, Regional Director for Sustainable Development, South Asia

As the global community coalesces to draft an international, legally-binding treaty to reduce plastic pollution by 2024, we need to think about what to do with the plastic waste we have already generated. The use of plastic waste in roads may be one possible option to apply this waste in a manner that may also reduce carbon emissions.

Valerie Hickey, Global Director, Environment, Natural Resources and the Blue Economy

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The use of plastic waste in roads is an emerging technology spreading worldwide, through either pilot projects or roads that are in use. This first of a kind World Bank report, *Plastic Waste in Road Construction: A Path Worth Paving?* puts a spotlight on the possibility of incorporating plastic waste in road construction.

Nicola Peltier, Global Director, Transport

Plastic pollution is a significant issue in South Asia, threatening human and environmental health. I'm happy to hear of this emerging method to construct roads using plastic waste, which may otherwise end up in open dumps or the environment. Of course, there is no silver bullet, and we need to ensure that we do no harm if applying such technologies.

Guangzhe Chen, Vice President, Infrastructure

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Glossary of Terms

Aggregate gradation: The particle size distribution from the largest through finest materials.

Aggregate: A hard inert material of mineral composition such as sand, gravel, slag, or crushed stone of various sizes, used in pavement applications either by itself or for mixing with asphalt binder.

Air pollutants: Those impurities which cause the atmosphere to become contaminated. These include carbon monoxide, nitric oxides, sulfur dioxides, particulates, and hydrocarbons.

Alternative material: a material to those traditionally used in construction, typically it may be an industrial by product, a recyclable, a treated material, and so on.

Asphalt binder or asphalt cement: A dark brown to black cementitious material which predominantly constituted of bitumen which occurs in nature or is obtained in petroleum processing. Asphalt is a constituent in varying proportions of most crude petroleum.

Asphalt binder: Asphalt cement that is classified according to the Standard Specification for Performance Graded Asphalt Binder, AASHTO Designation MP1. It can be either unmodified or modified asphalt cement, as long as it complies with the specifications.

Asphalt concrete: A high quality, thoroughly controlled mixture of asphalt binder and high-quality aggregate, which can be compacted into a uniformly dense mass.

Asphalt emulsion mix (cold): A mixture of unheated mineral aggregate and emulsified (or cutback) asphalt binder. It can be plant-mixed or mixed in-place.

Asphalt pavement: Pavement consisting of a surface course of asphalt concrete over supporting courses such as asphalt concrete bases, crushed stone, slag, gravel, Portland Cement Concrete, brick, or block pavement.

Asphalt: Mixture of aggregate and fine particles held together in a bitumen-based binder. Also known as asphaltic concrete in many countries.

Asphalt(ic) cement: Brownish black, solid or semisolid mix of bitumen from native deposits or a petroleum by-product used in the manufacturing of asphaltic concrete.

Average daily traffic: Measurement of the number of vehicles using a highway over a year divided by 365 to obtain the average for a 24-hour period.

Base: The main structural layer of a pavement.

Bitumen: A natural asphalt or substance found in a natural state or a residue by-product from petroleum refinement.

Bituminous: Containing bitumen.

Cement: A powdered product made by grinding clinkers of limestone, clay, and other materials, and which reacts with water to form a rock-like substance used to bond aggregates together in concrete.

Cold mix asphalt: A mixture of emulsified or cutback asphalt and aggregate produced in a central plant (plant-mixed) or mixed at the road site (mixed-in-place). Cold mix asphalt can be produced and stored for usage at a later date.

Concentration: The amount of a substance expressed as a proportion of the water, air, or solid in which it resides. Usually expressed as mass of substance per volume of liquid or as mass of substance per mass of solid.

Concrete: A material formed of aggregate bound together with Portland cement. Also known as Portland cement concrete.

Construction and Demolition (C&D) Waste: Material including concrete, bricks, lumber, masonry, road paving materials, rebar and plaster generated from both homeowners' and contractors' construction or demolition projects.

Contaminant: A chemical, microorganism, or particulate component that is normally absent from the environmental compartment in which it resides, or which is present at an elevated concentration.

Crack: An approximately vertical random cleavage of the pavement caused by traffic loading, thermal stresses and/or aging of the binder.

Deflection: A load-induced, downward movement of a pavement section.

Dispersion: The three-dimensional redistribution of a substance dissolved or suspended in a fluid that is caused by local variations in movement of that fluid usually resulting from inhomogeneity in the pathway.

Dry process: Plastic waste is shredded and mixed with preheated aggregates prior to adding bitumen at 160°C.

Durability: The property of an asphalt paving mixture that represents its ability to resist disintegration from the environment and traffic.

Elastomer: Polymer that displays elastic mechanical properties.

Emulsifying agent or emulsifier: The chemical added to water and asphalt that keeps the asphalt in stable suspension in water. The emulsifier determines the charge of the emulsion and controls the breaking rate.

Fatigue and Cracking Resistance: The ability of asphalt pavement to resist crack initiation caused by repeated flexing.

Flexibility: The ability of an asphalt pavement structure to conform to settlement of the foundation.

Hot mix asphalt: High quality, thoroughly controlled hot mixture of asphalt binder (cement) and well-graded, high quality aggregate, which can be compacted into a uniform dense mass.

Human carcinogen: Substance that promotes the formation of cancer in humans.

Liquefaction: Process of making or becoming a liquid.

Mechanical recycling: Operations that recover plastics through mechanical processes, including grinding, washing, separating, drying, re-granulating and compounding.

Microplastics: Plastic pieces less than 5 millimeters (0.2 inches) in length that occur in the environment as a consequence of plastic pollution.

Modified asphalt rubber binder: Conventional asphalt cement to which recycled ground tire rubber and compounds have been added, that when reacted with the hot asphalt cement causes a dispersion of the tire rubber particles and compounds.

Patching: When the pavement begins to deteriorate due to the influences of the environment and traffic, holes, ruts and cracks are usually localized at existing pavement joints. The repair of this type of failure consists of sawing out, removing and replacing the material with new Portland cement concrete or bituminous concrete.

Pavement: Any layer added to the natural ground surface, The part of a roadway having a constructed surface for the facilitation of vehicular movement.

Penetration: The consistency of a bituminous material expressed as the distance (in tenths of a millimeter) that a standard needle penetrates a sample vertically under specified conditions of loading, time and temperature.

Performance grading: Asphalt binder grade designation used in Superpave. It is based on the binder's mechanical performance at critical temperatures and aging conditions.

Phase separation: Separation between the recycled plastic and binder in road construction that occurs under static heated storage conditions which can affect road performance negatively.

Plasticizer: Substance added to synthetic resin to promote plasticity and flexibility and to reduce brittleness.

Plastomer: Type of modifier used to prevent rutting and increase viscosity of modified binder.

Poise: A centimeter-gram-second unit of absolute viscosity equal to the viscosity of a fluid in which a value of stress one dyne per square centimeter is required to maintain a difference of velocity of one centimeter per second between two parallel planes in the fluid that lie in the direction of flow and are separated by a distance of one centimeter.

Pollutant: A substance existing at sufficient concentration such that its effects are harmful to human health, other living organisms, or the environment.

Polymer-modified asphalt binder: A conventional asphalt cement to which a styrene block copolymer or styrene butadiene rubber latex or neoprene latex has been added to improve performance.

Post-consumer plastic waste: The status after an item has been used for its intended purpose. Postconsumer material may be generated by households or commercial establishments.

Post-industrial plastic waste: Material that has been processed initially and failed to meet specifications or otherwise not sold as prime material and sold to another party for reuse or reprocessing.

Pyrolysis: Thermal degradation of plastic waste to produce liquid oil.

Raveling: The progressive separation of aggregate particles in a pavement from the surface downward or from the edges inward.

Reactive polymer: A polymer having chemical groups that can be transformed into other chemical groups under the specific conditions required for a given reaction or application.

Reclaimed asphalt pavement (RAP): Excavated asphalt pavement that has been pulverized, usually by milling, and is used like an aggregate in the recycling of asphalt pavements.

Reclaimed asphalt shingles: Discarded roofing shingles that are used like an aggregate in the recycling of asphalt pavements.

Recycled asphalt mix: A mixture produced after processing existing asphalt pavement materials. The recycled mix may be produced by hot or cold mixing at a plant, or by processing the materials cold and in-place.

Recycling: Separating, collecting, processing, and reprocessing, often either chemically or mechanically, of a material for use in a new material or product.

Rutting: Channeled depressions that sometimes develop in the wheel paths of an asphalt pavement.

Shoving: A type of pavement distortion. These distortions usually occur at points where traffic starts and stops, on hills where vehicles brake on the downgrade, on sharp curves, or where vehicles hit a bump and bounce up and down. They occur in asphalt layers that lack stability.

Skid resistance: The ability of an asphalt paving surface, particularly when wet, to offer resistance to slipping or skidding. The factors for obtaining high skid resistance are generally the same as those for obtaining high stability. Proper asphalt content and aggregate with a rough surface texture are the greatest contributors. The aggregate must not only have a rough surface texture, but also resist polishing.

Solubility: A measure of the purity of asphalt cement. The ability of the portion of the asphalt cement that is soluble to be dissolved in a specified solvent.

Stability: The ability of an asphalt paving mixtures to resist deformation from imposed loads. Stability depends on both internal friction and cohesion.

Superpave Mix Design: An asphalt mixture design system that integrates the selection of materials (asphalt, aggregate) and volumetric proportioning with the project's climate and design traffic.

Superpave™: Short for "Superior Performing Asphalt Pavement" – a performance-based system for selecting and specifying asphalt binders and for developing an asphalt mixture design.

Virgin polymer: Polymer resin produced from petrochemical feedstock, such as natural gas or crude oil, which has never been used or processed before.

Viscosity grading: A classification system of asphalt cements based on viscosity ranges at 60°C (140°F). A minimum viscosity at 135°C (275°F) is also usually specified. The purpose is to prescribe limiting values of consistency at these two temperatures. Approximately 60°C (140°F) is the maximum temperature of an asphalt pavement surface in service in the United States. Approximately 135°C (275°F) is the mixing and laydown temperatures for hot mix asphalt pavements.

Viscosity: A measure of the resistance to flow of a liquid. It is one method of measuring the consistency of asphalt.

Waste nitrile rubber: Synthetic rubber made from a copolymer of acrylonitrile and butadiene.

Wearing Course: Top layer of an asphalt structure that is designed to accommodate traffic load and resist skidding and adverse weather.

Wet process: Recycled plastics in the form of powder are added to bitumen, heated at 160–170°C, mechanically mixed, and then the aggregate is added.

Acronyms and abbreviations

AASHTO: American Association of State Highway and Transportation Officials

ABI: Abstracted Business Information

ABS: Acrylonitrile–Butadiene–Styrene

APP: Ammonia Polyphosphate

ASTM: American Society for Testing and Materials

Cd: Cadmium

CO_2: Carbon dioxide

Cr: Chromium

Cu: Copper

CEA: Cost-effectiveness analysis

CSIR: Central Road Research Institute, India

EEE Index: Energy, Environmental and Economic Index

EVA: Ethylene Vinyl Acetate

GMA: Glycidyl Methacrylate

HAP: hazardous air pollutants

HDPE: High-Density Polyethylene

IDT: Indirect Tensile Test

INR: Indian rupee

IRC SP: Indian Roads Congress Special Provision

KHRI: Kerala Highway Research Institute

KPMG: Klynveld Peat Marwick Goerdeler

LAST: Laboratory Asphalt Stability Test

LCA: Life Cycle Assessment

LLDPE: Linear low-density polyethylene

LDPE: Low-density polyethylene

LSGD: Local Self Government Department, Kerala, India

MMT: Million metric tons

MoEFCC: Ministry of Environment, Forest, and Climate Change, Government of India

MoRd: Ministry of Rural Development, Government of India

MoRTH: Ministry of Road Transport and Highways, Government of India

NCAT: National Center for Asphalt Technology

NHAI: National Highway Authority of India

Ni: Nickel

NJDOT: New Jersey Department of Transportation

Pb: Lead

PC: Polycarbonate

PE: Polyethylene

PET: Polyethylene terephthalate

PP: Polypropylene

PPA: Polyphosphoric acid

PS: Polystyrene

PV: Present value

PVC: Polyvinyl chloride

PWD: Public Works Department

RAP: Reclaimed Asphalt Pavement

RET: Reactive elastomeric terpolymer

RIC: Resin identification codes

S&P: Standard and Poor

SAR: South Asia Region

SDBC: Semi-dense bituminous concrete

SBS: Styrene–Ethylene–Butylene

SLRM: Solid liquid resource management

SWIS: Solid Waste Institute for Sustainability

SIS: Styrene–Isoprene–Styrene

SWaCH: Solid Waste Collection and Handling

TxDOT: Texas Department of Transportation

UK: United Kingdom

UNEA: United Nations Environment Assembly

US: United States

USHRP: United States Strategic Highway Research Program

Zn: Zinc

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Abstract

As global plastic waste continues to grow, the global community is coalescing to reduce plastic waste. Some stakeholders are also exploring new options to use plastic waste as partial substitute for raw material. The use of plastic waste as a bitumen modifier in road construction, referred to here as 'plastic roads', is one option being explored. We reviewed the scientific literature, news articles, and patents; conducted a cost-effectiveness analysis; and interviewed representatives from private companies and independent, scientific researchers to determine the existing knowledge gaps regarding the (1) technology feasibility, including engineering performance; (2) environmental issues; (3) occupational health; (4) economic viability; and (5) industry standards surrounding plastic roads. We found that many companies are starting to implement or pilot this technology worldwide though key gaps in engineering performance, such as cracking resistance, remain. The environmental issues reviewed also have research gaps, including the generation of hazardous air pollutants during production; microplastics and nanoplastics generation during use; and leaching of additives from plastic waste during use. Industry standards for the use of plastic waste in road construction are lacking. In addition, there is prevailing uncertainty in the economic viability of the technology. As a result of these key research gaps, the Ways Forward section presents a roadmap for short- and long-term research priorities.

Executive summary

Plastic pollution is one of the most pressing environmental issues globally. Plastics were commercialized in the 1950s (Andrady and Neal 2009) and have grown to be ubiquitous in our everyday lives, becoming the most widely used man-made substance (Worm et al. 2017). In a business-as-usual scenario, the amount of plastic waste produced will grow from 220 million metric tons in 2016 to an estimated 430 million metric tons in 2040 (The Pew Charitable Trusts and SYSTEMIQ 2020). In South Asia, open dumping (75 percent) dominates, while recycling (5 percent), and landfilling[1] (4 percent) (Kaza et al. 2018) are less frequently used. Given the large amounts of plastic waste produced globally, entrepreneurs, innovators, and researchers are discovering new ways of utilizing plastic waste.

The use of plastic waste in road construction is an emerging, more recent alternative use of plastic waste. Plastic roads were patented as early as 1974 and have spread, especially throughout India since Dr. Rajagopalan Vasudevan reported this technology in the scientific literature in 2004. In plastic roads, post-consumer and/or post-industrial plastic waste is used as a partial substitute for aggregate or bitumen, often between 6 and 8 percent by weight of bitumen. In the wet process, powdered plastic waste is added to bitumen, heated, and then added to the aggregates. This report focuses on the dry process in which plastic waste is shredded and mixed with preheated aggregates prior to adding bitumen.

This report targets policy makers, the private sector, and transport practitioners who may be considering using plastic waste in road construction. The report aims to

- **a** **Provide an overview on the use of plastic waste in road construction using the dry process in South Asia, in comparison to conventional roads;**
- **b** **Summarize the environmental impacts, engineering performance, regulatory considerations and economic viability;**
- **c** **Recap the key challenges and knowledge gaps; and**
- **d** **Develop recommendations to inform further research and road infrastructure projects in South Asia.**

In the preparation of this report, the project team reviewed the scientific literature, news articles, and patents; conducted a cost-effectiveness analysis; and interviewed representatives from private companies and independent, scientific researchers studying the use of plastic waste in road construction. The key findings, identified by the proj-

1 The type of landfilling, whether controlled or sanitary landfilling, is unspecified (Kaza et al. 2018).

ect team, are clustered within this report into five themes: (1) technology feasibility, including engineering performance; (2) environmental issues; (3) occupational health; (4) economic viability; and (5) industry standards. Recommendations to address key knowledge gaps were identified.

Key findings

(1a) Technology feasibility: Plastic roads are an emerging technology. The dry process primarily faces quality control issues, such as uneven distribution of plastic waste within the asphalt mix. This results in operational issues for the industry and constraints in mainstreaming the technology. Similarly, additional and upgraded equipment would be needed to incorporate plastic waste into asphalt at the plant.

(1b) Engineering performance: Overall, there is currently high uncertainty in the field regarding the performance of plastic roads. Generally, the use of plastic waste in road construction improves rutting performance. However, improvements in rutting often lead to problems with road cracking. A few studies show that the use of plastic waste in road construction may reduce road cracking resistance. Long-term performance of plastic roads under a range of environmental conditions, including flooding, remains unclear. Without this certainty, it will be difficult to ensure that plastic roads will not require more maintenance than conventional roads.

(2) Environmental issues: Key gaps related to the environmental sustainability of this technology were identified and include the following topics: microplastics, additive leaching, recyclability at the end of life, and life cycle analysis. Further research in these areas will help determine the environmental sustainability of this technology.

(2a) Microplastics: The scientific field lacks key environmental studies on the scale and toxicity of microplastics and nanoplastics generated from plastic roads and tire wear as compared to conventional roads and tire wear. It is expected, but to our knowledge, not yet documented, that plastic roads will generate microplastics and nanoplastics from road and tire wear just as conventional roads do.

(2b) Additive leaching: Plastics leach organic and inorganic additives. Further research is also needed to determine if these additives leach from plastic roads and if so, what is the amount of additives leached and chemical compounds. It is unknown if construction techniques can mitigate this leaching. The toxicity of leached plastic additives to aquatic and terrestrial animals and environments should be evaluated.

(2c) Recyclability at the end of life: Most asphalt pavement in conventional roads can be recycled. It remains unknown if plastic roads can be recycled at the end of their lifespan. Further research should include end of life planning for plastic roads and determine if and how these roads can be recycled.

(2d) Life cycle analysis: Lastly, we identified studies that analyzed plastic roads in comparison to conventional roads from a life cycle perspective. However, these studies focused on roads in high-income countries. Further research that conducts a life cycle assessment (LCA) on plastic roads in lower-income countries is needed. This research incorporates the generation of greenhouse gas emissions as a part of the analysis.

(3) Occupational health: At the asphalt plant, the risk of fire and generation of hazardous air pollutants (HAP) can be high for plastic roads constructed using the dry process (Willis, Yin, and Moraes 2020). Plastics must be heated to combine the aggregate and this should only occur at the central asphalt plant with proper, protective environmental and occupational health guidelines, rather than in an informal setting. The heating of plastics can produce HAP such as volatile organic compounds and polycyclic aromatic hydrocarbons (Willis, Yin, and Moraes 2020). Occupational health standards should be created and have provisions to mitigate those risks.

(4) Economic viability: There are conflicting reports regarding whether or not plastic roads are more affordable than conventional roads. Often, plastic roads are reported to be more affordable than conventional roads since plastic waste often partially substitutes for bitumen (between 6 and 8 percent). We conducted a cost-effectiveness analysis that indicates that the use of waste plastic in road construction is economically justifiable. However, KPMG (2021) conducted a cost-benefit analysis for the World Bank and found that the use of plastic waste in road construction increases the cost of roads by US$0.14 per square meter of road, as compared to conventional roads. The Government of India's Ministry of Railways (2019) came to the same conclusion. Multiple engineering studies in the scientific literature presented short analyses regarding the costs of plastic roads compared to conventional roads. These studies primarily found that plastic roads were cheaper than conventional roads. The literature presents differing views on the economic viability of the use of plastic waste in road construction.

(5) Industry standards: At the time that this study was conducted, India was the only country that has adopted standards guidelines Indian Roads Congress Special Provision 98-2013 (IRC SP 98-2013) for the use of plastic waste in road construction. The United Kingdom is likely to issue standards in the near future. Widespread standards and guidelines on how plastic waste can be incorporated into roads are lacking.

Key knowledge gaps and standards regarding the viability of plastic roads are yet to be determined. Field and laboratory research, pilot projects, and public-private partnerships may help fill the aforementioned knowledge gaps on the use of plastic waste in road construction. **Table 1** shows through different color coding that most of the aspects of plastic waste use in road construction still experience knowledge gaps and require further research and in-depth analyses. Subcategories in green indicate topics with little uncertainty, which have been extensively researched. Subcategories in yellow indicate topics in which research was conducted, but major gaps still exist. Subcategories in red indicate topics in which there is a high uncertainty level.

Ways forward

The recommendations provided are organized by short- and long-term recommendations for further research. The achievement of the short-term recommendations will provide necessary prerequisites and input into the way the long-term recommendations should be pursued. These recommendations are specific to the use of plastic waste in road construction, but we also recommend that researchers investigate alternative ways to use plastic waste.

Table 1.

Technology readiness of plastic roads and level of uncertainty in existing knowledge gaps.

Technology readiness category	Subcategory
Technology feasibility and engineering performance	Projects implemented worldwide
	Industry players involved
	Road cracking resistance
Environmental issues	Life cycle analysis
	Generation of HAP when heating plastics[2]
	Additive leaching
	Recyclability of roads at end of life
	Generation of microplastics and nanoplastics
Economic viability	Cost-effectiveness analysis
	Lifespan of roads
	Cost-benefit analysis
	Supply of quality feedstock

Note: The following color scheme is used: green - little uncertainty, extensively researched; yellow - research was conducted, but major gaps still exist; and red - high uncertainty level.

2 The production of HAP is a major concern when heating plastics, but we expect that guidelines can be developed to protect occupational health from these pollutants.

Short-term research

We recommend that an interdisciplinary team of experts in plastic waste applications, environmental and occupation health, and pavement technology spanning private entities, public-private partnerships, and governments, conduct short-term research to fill the research gaps listed below. Based on the results of the short-term studies, interested stakeholders should determine if and how long-term research should be pursued.

Technology feasibility

- A gap exists in regard to the quality assurance and control and engineering performance parameters, such as unevenness and skid number (KPMG 2021), of the use of plastic waste in road construction.
- It is not known if the use of plastic waste in road construction results in increased road cracking, as compared to conventional roads.

Environmental issues

- **Microplastics:** Although conventional roads and tire wear are known contributors to global microplastic pollution, we were unable to identify a study on the generation of microplastics and nanoplastics from plastic roads and tire wear.
- **Additive leaching:** Further research should be conducted on organic and metallic additive leaching from roads, including how different plastic waste melting temperatures and road construction methods may or may not impact the leaching of plastic additives.
- **Recyclability at the end of life:** It remains unknown whether the plastic waste in roads can be recycled or if the entire plastic road, including the plastic waste and bitumen, can be recycled.

Long-term research

If supported by the short-term research, we recommend conducting long-term research and pilot projects to fill the research gaps listed below. We expect that a stocktaking of performance monitoring results from existing pilot projects and plastic roads will also be helpful. Field research and pilot projects should only be pursued if the short-term research results suggest that plastic roads are a viable option.

Technology feasibility

- Long-term studies on standard measures of road performance, such as road moisture susceptibility, filtrate management as well as engineering performance measures, such as cracking resistance, road moisture susceptibility, are greatly needed. These tests should be conducted under a range of environmental conditions, such as flooding, ultraviolet rays exposure, and extreme events, such as environmental accidents or natural disasters.
- The scalability of plastic roads needs to be determined and is likely be based on plastic waste quality and collection rates in an area, ability to increase the percentage of plastic waste used in roads, and the long-term performance of the plastic roads.

Environmental issues

- Further research is needed to analyze plastic roads from a life cycle perspective, including greenhouse gas emissions, in lower-income settings.

Occupational health

- Occupational health guidelines need to be created, which protect human health from the generation of HAP and prevent accidental fires at the asphalt plant (Willis, Yin, and Moraes 2020).

Economic viability

- Detailed cost-benefit analyses that are ground-truthed with data from the field should be conducted to determine if plastic roads are more expensive or cheaper than conventional roads over the long term.

Industry standards

- We recommend that industry standards be determined to clarify the method used to incorporate plastic waste into bitumen as well as the amount and types of asphalt and plastic waste.
- Over 10,000 chemical compounds are associated with plastics, at least 2,400 of which have known toxicological issues (Wiesinger, Wang, and Hellweg 2021). Further work is needed to standardize the additives used in plastics.

The upcoming international, legally binding treaty to reduce plastic pollution calls for a 'full life cycle approach' to reduce plastic pollution, incorporating both upstream and downstream measures. The use of plastic waste in road construction is a downstream measure to utilize plastic waste as an input material; further upstream measures to reduce plastic waste are needed.

1 Introduction

Since plastics commercialization in the 1950s (Geyer, Jambeck, and Law 2017), global plastic production has skyrocketed, so much so that annual plastic production was almost equal to the combined weight of the global human population by 2015 (Worm et al. 2017). Plastic is ubiquitous in many aspects of our lives, such as clothes, food packaging, medical supplies, and construction materials. Plastics ubiquity has also grown in the environment as a global pollutant and has been found in some of the most remote corners of the Earth, such as deep-sea trenches and the atmosphere (Brahney et al. 2021; Evangeliou et al. 2020; Fischer et al. 2015).

Recently, governments at the United Nations Environment Assembly 5.2 agreed upon the resolution titled "End Plastic Pollution: Towards an internationally legally binding instrument" (IISD 2022). Through this resolution, the United Nations Environment Assembly (UNEA) will set up an Intergovernmental Negotiating Committee to negotiate an international, legally binding treaty to reduce plastic pollution across plastics life cycle by 2024 (IISD 2022; UNEP 2022a).[3] At present, measures implemented to reduce plastic pollution are not keeping pace with the rise in pollution. For example, even with immediate, coordinated, and drastic global action to reduce plastic pollution, 710 million metric tons of plastic are expected to enter the environment between 2016 and 2040 (Lau et al. 2020).

Innovations that utilize plastic waste as an input material have emerged, making use of the growing amounts of plastic waste produced (Dijkstra, van Beukering, and Brouwer 2021). The amount of plastic waste produced is expected to grow from 220 million metric tons in 2016 to 430 million metric tons in 2040 in a business-as-usual scenario (The Pew Charitable Trusts and SYSTEMIQ 2020). Thus, entrepreneurs, innovators, and researchers have begun to invent new technologies that utilize plastic waste as an alternative input material. Example businesses include those creating technologies to prevent plastic leakage into the environment (Schmaltz et al. 2020; Dijkstra, van Beukering, and Brouwer 2021), collect existing pollutants (Schmaltz et al. 2020; Dijkstra, van Beukering, and Brouwer 2021), transform recovered plastic waste into new materials, products, or energy (Dijkstra, van Beukering, and Brouwer 2021) and advance monitoring and assessment (Dijkstra, van Beukering, and Brouwer 2021).

The use of plastic waste as a bitumen modifier in roads, referred to here as plastic roads, has emerged as an innovation which uses plastic waste as an input material. In this technology, plastic waste is used to modify bitumen (less than 10 percent

3 Potential life cycle stages of plastic pollution encompassed in this approach may include extraction of raw materials, design and production; packaging and distribution; use and maintenance; disposal; and incineration and landfilling (UNEP 2022b). After use and maintenance, plastic may also enter the reuse and/or recycling life cycle phases, and will once again undergo design and production (UNEP 2022b).

bitumen replacement) in flexible pavement (Aziz et al. 2015; Nizamuddin et al. 2020). Virgin polymers have also been used to modify bitumen, aiming to reduce costs and improve road performance (Nizamuddin et al. 2020).

Since the use of plastic waste in road construction targets plastic waste after the use and maintenance stages, plastic roads are considered a downstream measure. Upstream measures that promote waste avoidance by targeting natural resource extraction and plastic production are greatly needed, as is suggested by the upcoming international treaty and the hierarchy of waste management that prioritizes prevention over reuse, recycling, energy recovery, and disposal (Lazarevic, Buclet, and Brandt, 2010). In addition to the upstream measures, we expect that some unavoidable plastic waste will be produced in the future, such as medical waste, so downstream measures that utilize plastic waste, such as recycling and upcycling, will be needed.

In this report, we aim to evaluate if the use of plastic waste in road construction is a viable option for the application of plastic waste that also protects environmental and human health. We met these goals by reviewing the scientific literature, news articles, patents; conducting interviews with business representatives and independent researchers in this field; and conducting a cost-effectiveness analysis (CEA). The key audience for this report are policy makers, researchers, and transport practitioners who are considering using plastic waste in flexible pavements. To evaluate if plastic roads are a viable option for plastic waste application, we collated available information to

a. **Provide an overview on the use of plastic waste in road construction (dry process) in South Asia, in comparison to conventional roads;**

b. **Summarize the environmental impacts, engineering performance, regulatory considerations, and economic viability;**

c. **Recap the key challenges and knowledge gaps; and**

d. **Develop recommendations to inform further research and road infrastructure in SAR.**

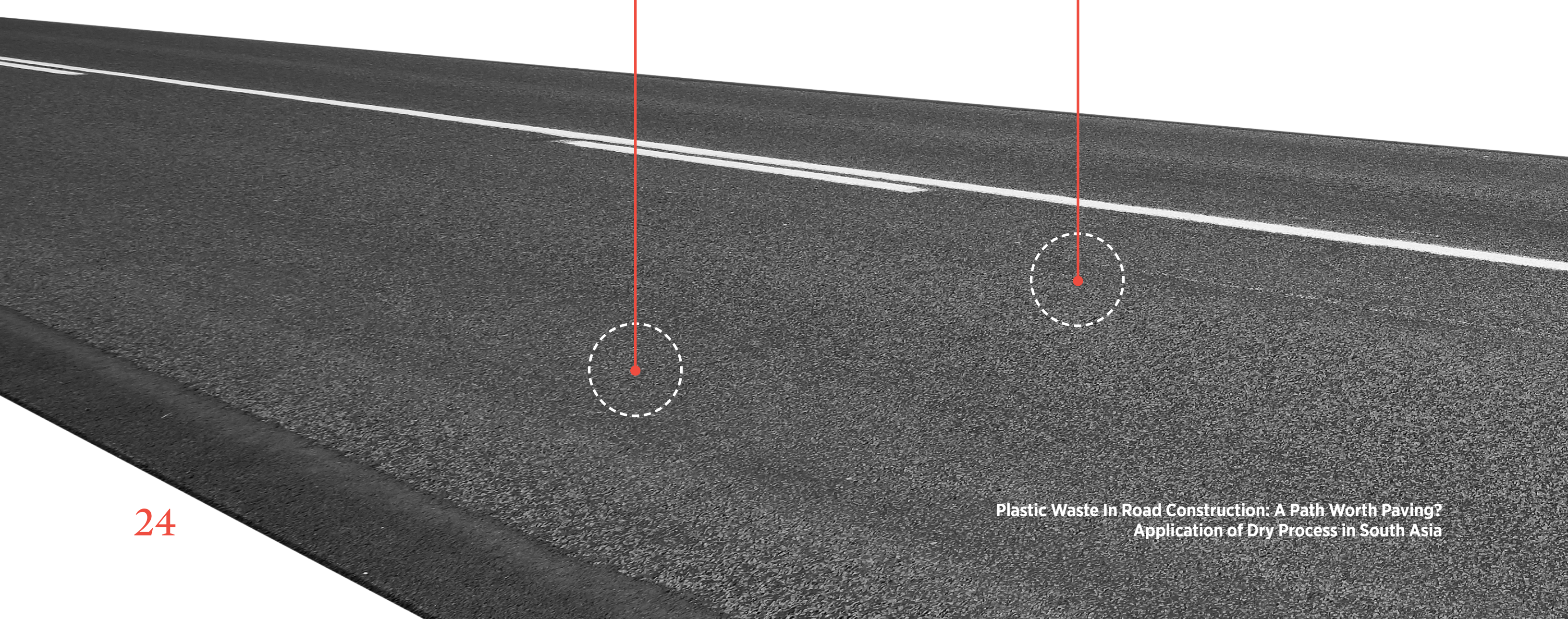
The methods used allowed us to summarize this technology in an evidence-based report. Detailed methods are available in **Annex A**.

This report has some limitations. Reports on the use of plastic waste in roads do not always specify if the roads are used in low-volume or high-volume traffic conditions (Sasidharan, Torbaghan, and Burrow 2019). Stocktaking of the traffic loads of existing plastic roads will further our understanding. Plastic roads need to be evaluated over different traffic loads and environmental conditions, including flooding. Technologies that focused on the use of plastic waste to replace concrete materials fall outside the scope of this report.

2 Methods

To prepare this report, the team reviewed the literature, including peer-reviewed articles, news articles, and patents; conducted semi-structured interviews of business representatives and independent researchers; and conducted a CEA. We conducted a review of news articles to find out where plastic roads have been implemented by reviewing news articles identified in the business news databases ABI Inform and Dow Jones Factiva by using a set of keywords. The following information was extracted from the news articles:

- Geographic location of road(s) by city (if available), country,
- Status of the road at the time of article publication (Select one: in use, planned/pilot/under construction, or planned, but dropped),
- Type of plastic item(s) (bags, bottles, other-specified, unspecified, tires) by count,
- Amount of plastic (kg or tons),



- Plastic recycling category (PET - 1, HDPE - 2, PVC - 3, LDPE - 4, PP - 5, PS - 6, Other - 7, Unspecified - 8),[4]
- Percent of bitumen,
- Name of company constructing the road,
- Name of government financing the road, if applicable,
- Name of development organization financing the road, if applicable, and
- Total project cost (US$).

4 The acronyms are defined as polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS).

Annex A provides a detailed summary of the methods used to prepare this report.

Plastic roads businesses were identified in news articles and the business database S&P Capital IQ. Business representatives ranging from engineers to founders to public relations contacts were interviewed to groundtruth our findings. Interview questions are presented in **Annex A**. Companies interviewed and their responses are presented throughout the report. We also interviewed two independent researchers who are studying the use of plastic waste in road construction at scientific and academic institutions. These researchers also reviewed the report for scientific accuracy.

To provide an overview of plastic roads technology, we used a set of keywords to search the Web of Science databases to find peer-reviewed articles that help us to understand plastic roads engineering performance, environmental issues, and economic viability. Articles were reviewed and data were extracted to help us answer the following questions: (a) what is plastic road technology? and (b) what are the environmental and economic benefits and downsides of implementing plastic roads? More than 500 articles were screened to find the relevant articles. Details on article screening methods and data extraction parameters are in **Annex A**.

We conducted a CEA to compare the costs of the business-as-usual scenario (bitumen road without plastic waste) to the cost of the intervention scenario (use of plastic waste in road construction). The scenarios and modelling assumptions were defined in detail. The CEA also includes the economic pricing of carbon, according to the World Bank's Guidance Note on Shadow Pricing of Carbon in Economic Analysis from 2017, and sensitivity analysis. The CEA can be found in detail in **Annex K**.

To better understand patented plastic roads technology, we conducted a search of plastic roads patents in the World Intellectual Property Organization's Patentscope database. Original patents were reviewed to collect the following information: year of patent filing and publication, inventor, patent applicant, type of plastic waste (post-consumer or post-industrial), recycling category of plastic waste, percent of bitumen comprised of plastic, and a hyperlink to the original patent in the Patentscope database.

Using the free, open-access database Plastic Policy Inventory (Diana et al. 2022; Karasik et al. 2020), we identified policies adopted in India that encouraged the use of plastic waste in road construction. Original policy documents were reviewed to determine if the sections describing plastic pollution reduction efforts referred to the use of plastic waste in road construction.

3 Road construction overview: the use of virgin polymer

Conventional road construction

Conventional road construction is primarily categorized as either flexible or rigid pavements (Aziz et al. 2015). Flexible pavements, which are bound with bitumen,[5] comprise 95 percent of highways found worldwide (Aziz et al. 2015; Rahman, Mohajerani, and Giustozzi 2020). Rigid pavements are less frequently used and are bound with Portland cement concrete (Aziz et al. 2015; Rahman, Mohajerani, and Giustozzi 2020). Flexible pavements comprise approximately 90–95 percent aggregate and about 5 percent bitumen (by weight) (APAI n.d.).

Bitumen is a by-product of crude petroleum that is used to coat and bind hot stones to build pavements (Vasudevan et al. 2012). As such, bitumen's price changes based on the price of petroleum and has generally been shown to increase over time: from US$61.95 per barrel in 2008 to US$97.98 in 2013 (Aziz et al. 2015). Bitumen comprises about 80 percent carbons, mainly aromatic hydrocarbons, and is black or brown in color (Aziz et al. 2015; Rahman, Mohajerani, and Giustozzi 2020). Bitumen is used in flexible pavement construction because it is waterproof and viscoelastic[6] (Aziz et al. 2015; Rahman, Mohajerani, and Giustozzi 2020). Viscoelastic materials are ideal for road construction since they regain their original shape after forces are applied from vehicles traveling on roads.

To reduce costs and improve road performance, alternative binders, such as polymers, bio-oils, waste materials, emulsions, and crumb rubber, have been substituted for bitumen in roads in three ways, which differ based on the percent of bitumen replaced and function of the substitute:

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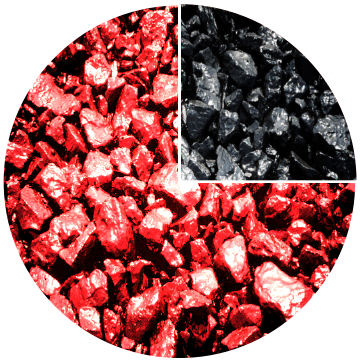
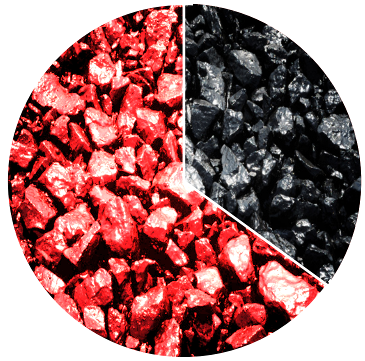
5 Bitumen is referred to as asphalt in the United States and Canada.

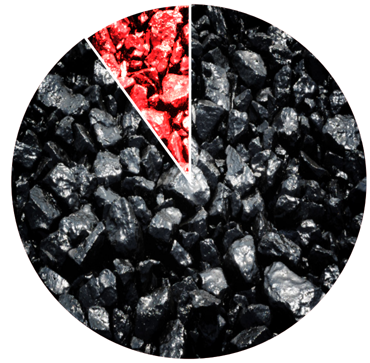
6 The viscoelasticity refers to the mechanical properties that are intermediate of viscous liquid and elastic solid (Tanzi, Farè, and Candiani 2019), which allows the pavement to deform in response to a force and then return to its original configuration (Gould et al. 2019).



a **Direct alternative** (75–100 percent bitumen replacement);



b **Bitumen extender** (10–75 percent bitumen replacement); and



c **Bitumen modifier** (<10 percent bitumen replacement) (Aziz et al. 2015; Nizamuddin et al. 2020).

Bitumen modifiers are widely used to improve pavement performance properties, such as durability, rutting resistance, softening point, and viscoelasticity (Aziz et al. 2015; Nizamuddin et. al. 2020; Vasudevan et al. 2012). The following virgin plastic additives are used to modify bitumen to enhance road performance: rubber latex, crumb rubber, styrene, butadiene styrene, styrene–ethylene–butylenes (SBS), recycled polypropylene (PP), low density polyethylene (LDPE), polyethylene (PE), ethylene vinyl acetate (EVA), and polyolefin (Vasudevan et al. 2012). SBS is by far the most common polymer additive in bitumen, at about 2 percent replacement.

Synthetic and natural polymers have been used to modify bitumen since 1843 with construction projects beginning in the 1930s in Europe and North America (Aziz et al. 2015). Polymer modification of bitumen is extensively practiced worldwide in high-volume roadways to enhance road performance by improving pavement elasticity, cohesion, moisture resistance, fatigue life, and performance at high temperatures by decreasing pavements resistance to deformation and low temperatures (Nizamuddin et al. 2020). Polyethylenes are thought to be some of the most effective bitumen modifiers to enhance rutting performance (Aziz et al. 2015; Nizamuddin et al. 2020), which decreases cracking performance (Willis, Yin, and Moraes 2020).

All polymers reduce thermal susceptibility of bitumen, such as rutting in warm temperatures and fatigue cracking in cold temperatures (Aziz et al. 2015; Nizamuddin et al. 2020). Specific polymer types may be used to modify bitumen to obtain certain desired properties. For example, reactive and plastomer polymers increase the stiffness and resistance to deformation due to traffic loads while elastomers improve elastic properties (resistance to fatigue) (Nizamuddin et al. 2020). Plastomers are often cheap and improve binder stiffness at high temperatures, which can result in resistance to permanent deformation.

Three polymer categories are used to modify bitumen: plastomers, elastomers, and reactive polymers (Nizamuddin et al. 2020). For example, polyphosphoric acid (PPA) is a polymer that has been used to modify bitumen. Others used with PPA are ethylene vinyl acetate copolymer (EVA), glycidyl methacrylate (GMA), Styrene–Isoprene–Styrene (SIS), PE, SBS, Ammonia Polyphosphate (APP), and Acrylonitrile–Butadiene–Styrene (ABS) (Aziz et al. 2015). Polymer properties influence which polymer is used in a given setting (Aziz et al. 2015).

Plastomers include the following plastic types: PE, polypropylene (PP), EVA, and ethylene-butyl acrylate or a combination of materials (Nizamuddin et al. 2020). PE is often referred to as the most effective plastomer and polymer bitumen modifier. It is well established that PE-asphalt binder modification improves performance by resisting fatigue and rutting as compared to unmodified roads (Nizamuddin et al. 2020). High density polyethylene (HDPE) and low-density polyethylene (LDPE) have been studied to determine which polyethylene better enhances road properties. HDPE (optimum at 12 percent by weight of bitumen) has been shown to enhance the properties of the pavement more so than LDPE by increasing road stability, reducing density, and increasing air and mineral aggregate voids (Aziz et al. 2015).

4 Use of plastic waste in road construction

Just as virgin polymer is used in road construction, recycled plastic waste has also been used been used in recent times, primarily to modify bitumen. Plastic waste can be used as a direct alternative to bitumen (75–100 percent bitumen replacement), bitumen extender (10–75 percent bitumen replacement), and bitumen modifier (less than 10 percent bitumen replacement) (Aziz et al. 2015; Nizamuddin et al. 2020). Plastic waste is most commonly used as a bitumen modifier (Willis, Yin, and Moraes 2020). Since bitumen constitutes about 5 percent of a flexible pavement road by weight (APAI n.d.), the use of plastic waste as a bitumen modifier, for example, would comprise about 0.5 percent of the total road. Unless stated otherwise, the term 'plastic roads' in this report refers to the incorporation of plastic waste into road construction as a bitumen modifier using the dry process. Multiple businesses and researchers are developing technologies that increase the amount of plastic waste used in roads, either as a direct alternative to bitumen or as a substitute for aggregate. PlasticRoads is an example of a business that uses plastic waste as a direct alternative to bitumen. In addition, the Solid Waste Institute for Sustainability at the University of Texas at Arlington is conducting studies on plastic waste as a substitute for aggregate (**Box 1**).

Plastic waste

Plastic waste broadly falls into two categories based on its source: post-consumer plastic waste and post-industrial/manufacturer's plastic waste. Generally, manufacturer's plastic waste is cleaner than post-consumer plastic waste and requires less sorting, making manufacturer's plastic waste easier to recycle (Willis, Yin, and Moraes 2020). Post-consumer plastic waste is collected from municipal solid waste drop-off locations, open dumps, or households (Willis, Yin, and Moraes 2020; Kaza et al., 2018). The plastic waste that we are referring to in this report primarily refers to post-consumer plastic waste.

Plastic waste can be categorized by the seven resin identification codes (RICs), which are based on the structure of the polymer backbone of plastics. The seven RICs, recyclability, example products, and percentage of the plastic waste composition in South Asia can be found in **Figure 1.** One physical property that varies between RICs is the melting point (**Annex Table 10**) (Willis, Yin, and Moraes 2020). This property is important for the incorporation of plastic waste into road construction because plastic is melted to coat the aggregate or mix with the binder (Willis, Yin, and Moraes 2020). About 9 percent of plastic waste produced between 1950 and 2015 was recycled (Geyer, Jambeck, and Law 2017). Although some plastic waste can be recycled multiple times successively (Eriksen et al. 2019; Geyer, Jambeck, and Law 2017), 90 percent of the recycled plastic waste has only been recycled once; so in the current scenario, recycling delays rather than avoids plastic disposal (Geyer, Jambeck, and Law 2017).

Figure 1.

Plastic RICs and amount consumed in kilotons in South Asia in 2018. The total plastic waste consumed domestically in South Asia is estimated to be 24,868 kilotons in 2018 (UN Comtrade 2021). Sources: CalRecycle (2021) and World Bank (2021).

		Plastic Resin Identification Code	South Asia region plastic consumption (kilotons in 2018)
	1	**Polyethylene terephthalate (PET)** Commonly recyclable Example products: soda bottles Recycled into many products (e.g., bottles, fibers)	2,561
	2	**High-density polyethylene (HDPE)** Often recyclable Example products: milk and juice bottles Recycled into many products (e.g., toys, trash cans)	3,126
	3	**Polyvinyl chloride (PVC)** Not commonly recycled Example products: house flooring, pipes, garden hoses, house siding	4,533
	4	**Low density polyethylene (LDPE)** Not commonly recycled Example products: cellophane, disposable diaper liners	3,670
	5	**Polypropylene (PP)** Not commonly recycled Example products: packaging, tubes, textiles	7,635
	6	**Polystyrene (PS)** Commonly referred to as "Styrofoam" Example products: coffee cups, food containers/ packaging, egg cartons Can be recycled, but not common	830
	7	**Other** Not commonly recycled Includes all plastic reins other than 1-6 and/or mixtures of resins	3,001

The Indian Roads Congress (IRC 2013) recommends the use of LDPE, HDPE, PET, and PU (RIC 7, Other) plastic waste in road construction (dry process), thus including both recyclable and some not commonly recycled plastics. In India, the adoption of an extended producer responsibility law (PTI 2022) may shift the plastic waste used in roads to be only those plastics that are unrecyclable. LDPE is one of the plastics currently recommended by the IRC to be used in road construction, and this plastic is not commonly recycled. The potential for incorporation of otherwise non-recyclable plastics into road construction makes plastic roads a potentially helpful option for the application of plastic waste. Further research is needed to ensure that the quality of plastic waste used in road construction does not compromise environmental and human health.

Plastic waste is a complex cocktail of chemical contaminants (Rochman et al. 2019). Although the chemical backbone of the plastics within a recycling category is the same, plastics contain chemical additives that are not standardized within or between recycling categories (Rochman et al. 2019). Additives are used in plastics, at about 7 percent of plastic by mass (Geyer, Jambeck, and Law 2017), to provide useful and desirable properties, such as elasticity and color. Since these additives are not strongly bonded to the polymer, plastics can readily leach additives into the surrounding environment (Li et al. 2016; Wright and Kelly 2017). A sample of plastic additives that make up to the 2,000 million metric tons (MMT) of plastic additives expected to be produced by the end of 2050 (Geyer, Jambeck, and Law 2017) can be found in **Annex B, Table 11**. These include plasticizers, flame retardants, stabilizers, antioxidants, fillers, impact modifiers, colorants/pigments, lubricants, and other additives such as biocides. Recent estimates note that over 10,000 compounds are associated with plastics, many of which have unknown health effects—about 2,400 have known toxicity concerns (Wiesinger, Wang, and Hellweg 2021).

Plastic waste must pass quality standards and undergo sorting, decontamination, shredding, and potentially washing prior to mixing with aggregate at the asphalt plant. To ensure that the correct plastic type is used in road construction, plastic must undergo collection and sorting by RIC. Plastic may be collected from multiple locations, including landfills, dumps, and the environment. In addition, plastic must undergo chemical and biological decontamination and potentially further washing (Willis, Yin, and Moraes 2020). During mechanical recycling, plastic also needs to be shredded, which allows the plastic to pass through sieve mesh sizes in millimeter (mm) ranges (Gopinath et al. 2020), noted to be 2.50–4.36 mm by Vasudevan et al. (2012). Shredded, decontaminated plastic may undergo further sorting based on separation properties and quality control measures, such as density, melting point, and color (Willis, Yin, and Moraes 2020).

Shredding plastic waste into smaller sizes increases plastics surface area and enhances binding between the plastic and bitumen (Gopinath et al. 2020). The aggregate is heated to 170°C and then the shredded plastic is placed over the heated aggregate, which then softens and coats it (Gopinath et al. 2020). A comparison between the use of plastic waste in road construction and conventional road construction, which often incorporates virgin plastic, can be found in **Figure 2**.

Only plastic waste that meets quality control standards can be used to modify bitumen, which must occur at the central asphalt plant. Robust specifications on the recycling processes required and properties of the recycled plastic for incorporation into asphalt pavements is lacking in most cases (Willis, Yin, and Moraes 2020). The IRC (2013) standards "Guidelines for the Use of Waste Plastic in Hot Bituminous Mixes (dry process) in Wearing Courses" provides a starting point that can be rigorously evaluated to create standards. The IRC (2013) guidance notes that plastic waste must be collected, cleaned, and shredded in a shredding machine and mixed with aggregate and bitumen at the central mixing plant. These standards provide specifications on the size, chemical specifications like dust and impurities and melt-flow value, and recycling category/type of plastic waste that can be safely used in asphalt in order to promote decent working conditions for those involved in this sector.[7] Further discussion of these standards is provided in the Regulatory Landscape section and a sample of the text is shared in **Annex D**.

Further research will be needed to determine plastic quality standards and methods of plastic waste incorporation to best protect human and environmental health.

7 PVC and black colored plastic waste is not recommended Indian Roads Congress Special Provision 98-2013 (IRC SP 98-2013).

Figure 2.

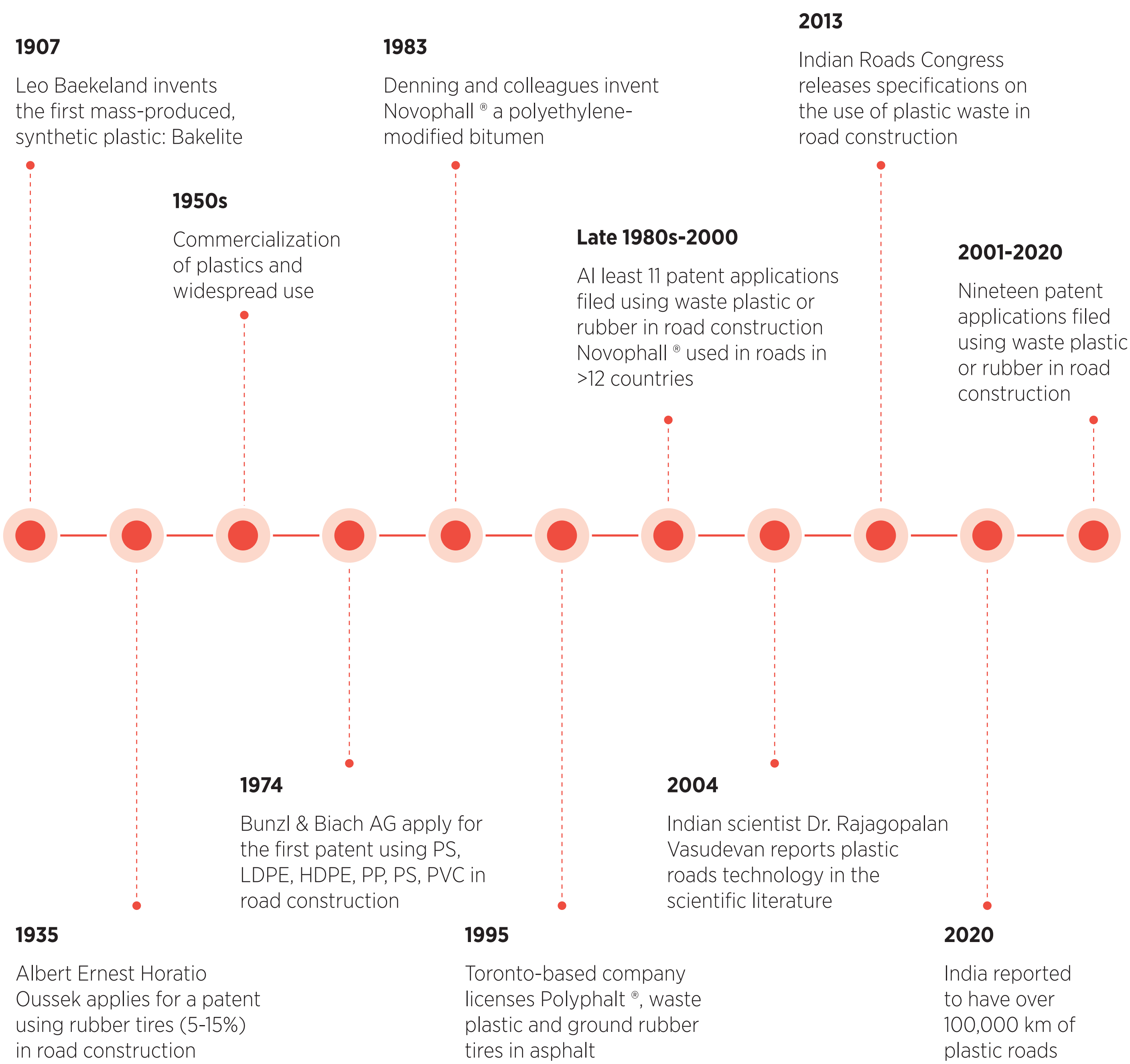
Process of building a conventional road or plastic road (wet and dry process). Each of the plastic waste processing steps has costs associated that are discussed in the Economic Analysis section.

Plastic roads

A brief history of key events in the invention of plastic and later the use of plastic and rubber tire waste in road construction is shown in Figure 3. Plastic was first invented in the early 1900s and gained widespread commercialization and use in the 1950s. To our knowledge, the first patent filed for the use of plastic waste (excluding rubber) in road construction was in 1974 by Bunzl & Biach AG in the United Kingdom. A little under fifty years later, India is reported to have 100,000 km of plastic roads. Patent applications for plastic waste increased between 1935 and June 2017(**Annex B, Figure 6**).

Figure 3.

Timeline of key events. Sources include patents and Denning and Carswell (1983); Mercer (1997); Willis, Yin, and Moraes (2020).



Composition and method of plastic waste used in road construction

Recycled plastic waste is incorporated into asphalt for road construction in one of two methods: (1) wet process or (2) dry process. Plastic waste can be mechanically or chemically recycled prior to incorporation into the asphalt. A brief description of the wet and dry processes, the role of the plastic waste, plastic types used, and estimates of the amount of plastic per 1 km of road can be found in **Table 3**.

Barriers exist that make it difficult to ensure the quality of plastic roads. For example, when using the wet process, phase separation between the plastic and binder is an engineering problem (Vasudevan et al. 2012; Willis, Yin, and Moraes 2020). However, some companies, such as Neo, have reported that that their roads do not undergo phase separation due to technological advancements (Box 1). Phase separation changes the physical properties of the pavement (Nahar 2016). The use of agitated storage tanks at the plant have been noted as a method to prevent phase separation; however, agitated storage tanks are not widely available to contractors (Willis, Yin, and Moraes 2020) and the financial risk of investing in these tanks for an emerging technology is high. As such, either a technological change that avoids phase separation or accessibility to the agitated storage tanks may help to break down this barrier. Quality control and assurance is greatly needed to ensure that the plastic is uniformly distributed in the tank during storage as well as in the road when laid for paving (Willis, Yin, and Moraes 2020).

Table 3.

Wet and dry process of plastic road construction. Sources include Gill and Abid 2019; Willis, Yin, and Moraes 2020; and the IRC (2013) specifications.

Method of incorporating plastic	Description of method	Role of plastic	Plastic types	Plastic (tons) per 1 km of road[8]
Wet process	Recycled plastics in the form of powder are added to bitumen, heated at 160–170°C, mechanically mixed, and then aggregate added	Polymer modifiers, asphalt replacement	Linear low density polyethylene (LLDPE), LDPE, HDPE[9]	0.48–1.9
Dry process	Plastic waste is shredded and mixed with preheated aggregates prior to adding bitumen at 160°C	Binder modifier, mixture modifier, aggregate replacement or a combination	**Aggregate replacement**: PP, PET, PS, PC[10] **Mixture modifier**: any plastic type other than PVC[11] in most cases	0.95–4.52

8 The amount of asphalt that is needed to construct a 1- km road will vary based on the width and depth of the road. These factors can vary across geographies and across types of roads (for example, low volume or high volume). Assuming a standard asphalt density of 2,322 kg/m^3, 1 km of road with a width and depth of 1.2192 m (4 feet) and 0.1524 m (6 inches) is roughly thought to weigh about 475.72 tons. We also assume an estimated weight of plastic as between 2-8 lbs/1 ton of asphalt for wet process and 4-19 lbs/1 ton of asphalt mixture for dry process. These calculations are rough estimates based on Georgiev, n.d., Gill and Abid 2019; Willis, Yin, and Moraes 2020; and the IRC (2013) specifications and further details in Annex C.

9 These plastic types are used due to low melting points.

10 These plastic types are used due to high melting points.

11 PVC cannot be used due to the concern of chloride and dioxin emissions. Box 1 features a research development by Behl, Sharma, and Kumar (2014) at the Central Roads Research Institute that has utilized PVC in road construction.

Plastic waste should only be incorporated into asphalt at the central asphalt plant rather than an informal setting. Heating plastics can generate hazardous air pollutants such as volatile organic compounds and polycyclic aromatic hydrocarbons (Willis, Yin, and Moraes 2020). As such, the heating of plastics for incorporation into asphalt should only be conducted in a controlled occupational setting where guidelines and standards that protect human health have been established. The Solid Waste Institute for Sustainability at the University of Texas at Arlington is currently researching if it is possible to reduce the production of toxic fumes by heating plastic waste at temperatures below 200°C. Further research and verification is needed to confirm this.

Current asphalt plants are not set up to incorporate plastic waste. Further research and standards are needed to reduce the risk of fires at the asphalt plant (especially for the dry process) and generation of hazardous air pollutants while heating plastics (Willis, Yin, and Moraes 2020). In the dry method, recycled plastics are introduced to the asphalt at the central plant often through the recycled asphalt pavement (RAP) conveyor or the cold feed through which recycled plastics enter the drum, which holds gases up to 760°C, thus increasing the fire risk (Willis, Yin, and Moraes 2020). In the wet process, recycled plastics are added using the terminal blending or plant blending approach, avoiding the aforementioned fire risks (Willis, Yin, and Moraes 2020). Occupational training should be given so that construction workers can safely handle the waste. This may involve drafting technical manuals for the workers (Sasidharan, Torbaghan, and Burrow 2019).

Use of plastic roads in other regions

We found 132 total plastic roads projects worldwide (Figure 4). We did not include multiple projects that were occurring at the same stage (for example, constructed) in the same geographic location as to not potentially overcount. Just recently, Pakistan has also constructed its first plastic road in the capital city of Islamabad (Daily Pakistan Global 2021). Furthermore, recent research from the University of Texas at Arlington funded through the Texas Department of Transportation has piloted the use of plastic waste in road construction in raised highway beds (Halsey 2018). Since this technology is relatively new and most countries lack standardized guidelines, long-term outcomes remain unclear and further pilot and research projects are needed (Sasidharan, Torbaghan, and Burrow 2019).

Several businesses research, develop, pilot, and sell this technology. Businesses interviewed to compile this report have constructed plastic roads in the United States (Neo, Dow), Mexico (Dow, PlasticRoads), Colombia (Dow), Vietnam (Dow), and the Netherlands (PlasticRoads). A subset of companies partaking in business involving the use of plastic waste in road construction and the location of company headquarters or the arm of the company focused on plastic roads can be found in **Annex E**. A sample of companies and research institutes involved in the use of plastic waste in road construction can be found in **Box 1**.

Fifty-eight percent of plastic roads projects surveyed in news articles were in planning, pilot, or construction phases at the time of source article publication while 37 percent reported were already constructed and in use (Figure 5). The 5 percent of projects that were planned but were dropped were for roads that would have been in Arraiján, Panama; Bengaluru, India; Doon, Dehradun, India; Mumbai, India; San Carlos, Chiriqui, Panama; and Thiruvananthapuram, India.

Figure 4.

Map of plastic roads.

Note: Sources for points on the map are in **Annex E**.

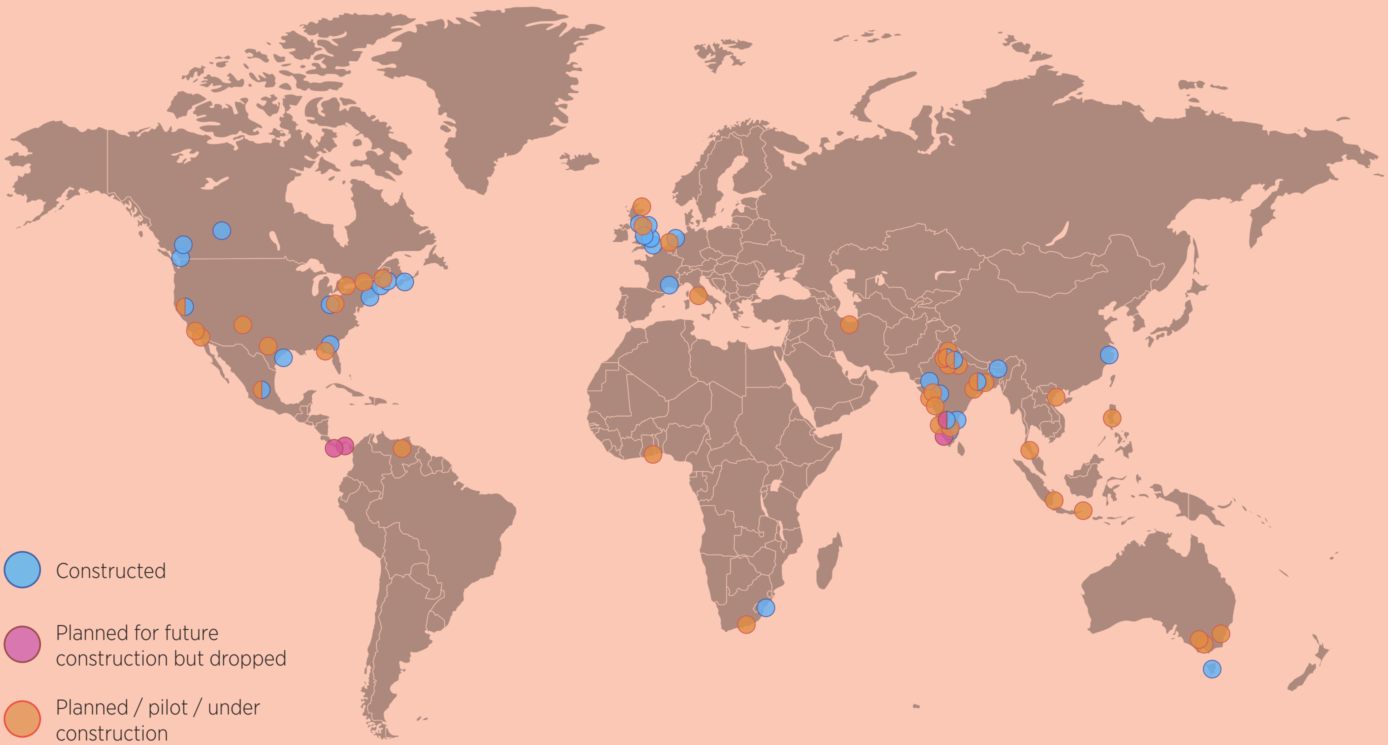
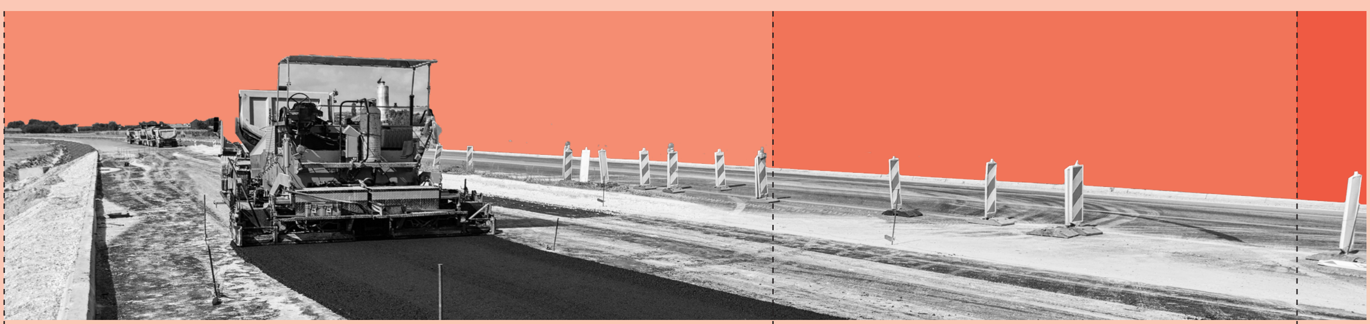


Figure 5.

Plastic roads use status.[12]



56%
Under construction/planned for future construction/pilots and trials

38%
Constructed

5%
Planed for the future but dropped

12 We reported projects as 'In use' if they were noted to be complete at the time of news article publication. Completed projects could not be undergoing pilots or trials. We grouped pilot projects, projects under construction, and projects planned where it was unclear if construction necessarily started or not into one group: 'Planned/pilot/in construction'. These three categories were grouped together since this level of detail was often not shared in the news articles reviewed. Projects that were planned, but dropped are also noted as 'Planned, but dropped'.

Box 1.
Sample of companies and research institutes

Central Roads Research Institute

The Central Roads Research Institute, a prestigious laboratory in India, recently patented a PVC-modified bitumen, using particular types of medical and pipe waste (Behl, Sharma, and Kumar 2014). Initial tests indicate that this new technology can be used as pavement. Further partnerships with bitumen manufacturers will provide insight into the scalability of this technology and the locations where it may be piloted.

The Dow Chemical Company

The Dow Chemical Company, often referred to as Dow, has been developing asphalt modifiers from plastic waste. For example, Dow has been a leader in this technology since it began demonstration projects in 2018. Over 300 kilometers of plastic roads have been built by Dow across all continents. Dow uses an ELVALOY™ reactive elastomeric terpolymer (RET) mixed with post-consumer recycled plastic waste content to modify the asphalt and reduce road resurfacing needs.

Neo

The United States-based company Neo has developed a method of converting PET to polyurethane elastomer, which can chemically bind to the rock. As such, Neo does not appear to be facing the phase separation issues noted when incorporating plastic into asphalt using the wet process.

PlasticRoads

Based in the Netherlands, the company PlasticRoads uses locally sourced recycled polypropylene as a direct alternative to asphalt pavement (almost 100 percent bitumen-replacement). PlasticRoads blocks are made almost entirely of plastic except for a thin coating of stone mineral to avoid abrasion and wear directly on the recycled plastic. This technology reduces carbon dioxide emissions and costs by about 52–70 percent and about 50 percent, respectively, in comparison to conventional roads. To address runoff, PlasticRoads has included a filtering mechanism to remove abrasion particles from infiltrating water that may enter the topsoil. PlasticRoads has six pilot projects in the Netherlands and one pilot in Mexico City.

Solid Waste Institute for Sustainability at the University of Texas at Arlington

Research at the Solid Waste Institute for Sustainability (SWIS) have found that plastic can be used as a base and subbase course material, substituting between 5 and 10 percent of aggregate in pavement (unpublished research). This development would increase the amount of plastic waste used in road construction by 10–20-fold.

Wenger Manufacturing and Enviroplaz

Although the focus of this report is on the use of plastic waste in flexible, bituminous pavement construction, Wenger Manufacturing and Enviroplaz created Plazrok USA to use mixed unrecyclable plastics in substitution for stone aggregate in concrete materials (deemed 'Plazrok™') in precast concrete and blocks. Plazrok™ creates a market for unrecyclable plastics that also cuts construction transportation costs since the concrete is lightweight. Plazrok™ highlights other potential uses of plastic waste in construction more broadly, such as in pedestrian sidewalks.

About 5% of plastic roads projects that were planned were dropped. The reported reasons vary, including factors such as government support, economic issues, and plastic waste quality. In Panama, plastic roads were not constructed due to the lack of the government's approval of Bill 687, which would have authorized the use of recycled materials, including plastics, in secondary streets in Panama (Noticias Financieras 2019a). Reasons noted for stopping the project in Bengaluru, India were the costs of cleaning, sorting, and drying of plastic waste (Chakravorty 2019). Chakravorty (2019) also noted a lack of government support, despite the passing of a national law in India promoting the use of plastic waste in road construction and government-issued standards. The project planned in Doon, Dehradun, India was stopped for similar reasons. According to officials, the "unsegregated and low quality of plastic waste available to the PWD" was the primary deterrent (Jha 2019). In Thiruvananthapuram, India, the following economic issues were noted:

> *"…some local bodies, which spent Rs 5-9 lakh for purchasing machines, had not sold a single kilo of plastic for tarring in the past two years. Data obtained through RTI showed that around 15 local bodies, which spent Rs 5.19-Rs 9.82 lakh for purchase of shredders and baling machines, didn't sell shredded plastic between 2017 and 2019. Yet, LSGD tried to keep the system alive. Suchitwa Mission executive director reported in 2018 that the average daily expense to run plastic shredding unit was Rs 2,057.5, while the income was just Rs 1,095. Local bodies were asked to pay Rs 965 as viability gap fund for the first six months." (The Times of India 2019)*

5 Key findings and knowledge gaps

Although both the wet and dry processes can be used to construct plastic roads, each process has relative advantages and disadvantages. For example, phase separation of binder and plastic is a disadvantage of using the wet process that is not encountered in the dry process (Willis, Yin, and Moraes 2020). Dry process can encompass greater amount of plastic (tons per 1 km of road) than wet process (**Table 3**). However, dry process has the reported disadvantage of increasing the fire risk at the asphalt plant and generation of hazardous air pollutants if occupational guidelines are not in place.

Plastic roads in the pilot or construction stage are found on every continent other than Antarctica. However, all countries other than India currently lack plastic roads guidelines and standards. Most plastic roads are undergoing pilot tests, under construction, or planned for future construction at the time of news article publication. Only 5 percent of projects were planned for the future, but dropped. These projects were in India and Panama. Reasons attributed to dropping the project were lack of governmental approval (Panama), lack of governmental support (India), plastic waste quality (India), and economic viability (India).

Environmental sustainability

The sustainability of plastic roads encompasses the (1) life cycle analysis, (2) leaching of additives, (3) microplastics, and (4) end-of-life recyclability. These categories were chosen based on the availability of studies in the literature as well as environmental impacts that were thought to have a great impact on the sustainability of plastic roads.

Overall, the scientific literature suggests that the use of plastic waste in road construction is beneficial from a life cycle analysis perspective though key gaps exist regarding the leaching of plastic additives and generation of microplastics. Gopinath et al. (2020) conducted an analysis that created an Energy, Environmental and Economic (EEE) Index, comparing the following disposal methods in India: landfilling, recycling, pyrolysis, liquefaction, road construction and tar, and concrete. The best option according to the EEE Index was plastic roads and the use of plastic waste in concrete for buildings (Gopinath et al. 2020). These options performed well due to the:

"lack of harmful greenhouse gas emissions, the ease of localization and the high sustainability and durability of the produced material and the constructed roads and buildings, the existence of which significantly outweighs demerits such as the inability to recover expended energy" (Gopinath et al. 2020).

Others have also noted that the use of plastic waste in road construction reduces carbon dioxide emissions of up to 3 tons/km of road compared to conventional roads (Sasidharan, Torbaghan, and Burrow 2019; Vasudevan et al. 2012).

LCA Studies

Life cycle assessment (LCA)[13] is a valuable tool for understanding the environmental impacts of a product over its lifespan. Overall, environmental impact reductions were consistently found from the use of plastic waste in road construction and often depended on life span of the road. Further details regarding the LCA studies are summarized in **Annex F**.

The LCA studies reviewed were primarily in high-income countries in Europe (Spain and France) and one in Australia. Thus, a key gap appears to exist in geography, notably lacking countries in Latin America and the Caribbean, Middle East and North Africa, South Asia, and Sub-Saharan Africa regions. The lack of LCA studies identified in South Asia is particularly surprising given that India has been a leader in the construction of roads using plastic waste over the past 15 years (Biswas, Goel, and Potnis 2020; Willis, Yin, and Moraes 2020). The lack of LCA studies focusing on the use of PET waste is worth noting given that PET was the second most frequently studied plastic type (behind PE) in our report (**Annex B, Figure 7**).

Overall, the LCA studies reviewed (Lastra-Gonzalez et al. 2021; Santos et al. 2018, 2021; Vila-Cortavitarte et al. 2018) consistently showed an environmental impact reduction, including greenhouse gas emissions, from the use of plastic waste[14] in road construction with few exceptions (Santos et al. 2021). A review by Pouranian and Shishehbor (2019) summarized whether the use of recycled plastics in the production, construction, maintenance, and end-of-life phases were reported to be associated with positive, negative, or the same effects on emissions and energy, in comparison to conventional asphalt roads. Pouranian and Shishehbor (2019) found that the use of recycled plastics has both positive and negative environmental impacts on emissions and energy used during the aggregate production phase. However, environmental benefits in emissions and energy were noted during binder production for plastic roads (Pouranian and Shishehbor 2019). At the plant and during the construction phase, asphalt containing recycled plastics performed similarly for greenhouse gas emissions and energy as conventional asphalt (Pouranian and Shishehbor 2019). During the maintenance and end-of-life phases, plastic roads improved emissions and energy (Pouranian and Shishehbor 2019). Maintenance and end of life were noted to be dependent on the performance of the asphalt mixture (Pouranian and Shishehbor 2019). Notably, crumb rubber and recycled plastics decreased greenhouse gas emissions and energy consumption within the maintenance and end-of-life phases as compared to conventional asphalts and other asphalt mixtures evaluated: recycled asphalt pavement, recycled asphalt shingles, construction and demolition waste, copper and steel slag, and vacuum tower bottoms[15] (Pouranian and Shishehbor 2019). However, crumb rubber can contain hazardous compounds, such as polycyclic aromatic hydrocarbons and phthalates (Armada et al. 2022).

Leaching

Major knowledge gaps regarding the leaching of (1) inorganic and (2) organic chemicals from plastic roads exists. Leaching of additives from plastic waste is a chemical hazard. Sasidharan, Torbaghan, and Burrow (2019) note that toxic additives may leach while plastic waste is being cleaned, prior to incorporation into asphalt. Initial reports from conference papers indicate that leaching and fume emissions were not reported as issues for the UK company MacRebur's plastic waste (Sasidharan, Torbaghan, and Burrow 2019; White 2019) though further verification and research is needed.

A few studies have evaluated the leaching of metallic additives from plastic waste used in road construction. We identified two scientific articles

13 The International Organization for Standardization (ISO) standard 14040, which regulates LCA defines it as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."

14 PS, waste nitrile rubber, EVA, LDPE, HDPE, packaging.

15 Residue from vacuum distillation process in oil refining (Pouranian and Shishehbor 2019).

that evaluated the leaching of plastic additives: Fernandes, Silva, and Oliveira (2019a, b). The full list of the specific mixtures and heavy metal additives evaluated in both studies are given in **Annex G**. The asphalt mixtures studied include waste motor oil or recycled engine oil bottoms and one of three waste plastics: HDPE, SBS, or crumb rubber in varying percentages. Although these samples are not ideal due to the use of waste motor or engine oil bottoms, which is outside of the scope of this study, these studies are reported here due to limited other scientific literature identified on this topic.

Fernandes, Silva, and Oliveira (2019a) primarily found that leaching of certain heavy metals and elements is not beyond legal limits outlined in the Portuguese Decree-Law no. 183/2009. For Cadmiun (Cd), Chromium (Cr), Nickel (Ni), and Lead (Pb), the samples containing HDPE and styrene–ethylene–butylenes (SBS) had less than or equal to the same amount of each metal as the reference material (Fernandes, Silva, and Oliveira 2019a). Similarly, Fernandes, Silva, and Oliveira 2019b found that all mixtures tested below the Portuguese Decree-Law no. 183/2009 for the leaching of Cd, Cr, Copper (Cu), Ni, Pb, and Zinc (Zn). The study design and leaching data is summarized in **Appendix I**. Further research is needed to determine if heavy metal and element leaching is harmful to aquatic and terrestrial animals and ecosystems.

Our study did not identify any scientific articles researching the leaching of organic contaminants from plastic roads. However, interviews with researchers from the Kerala Highway Research Institute (KHRI) and Central Road Research Institute (CSIR) indicate that studies on the leaching of organic additives from plastic roads are ongoing. Organic additives comprise a high percentage of plastic by weight and have environmental and human health impacts; for example, plasticizers can be between 10–70 percent weight of additive by weight of plastic (Hahladakis et al. 2018). Phthalates function as plasticizers in plastic and are found in many consumer products (Grindler et al. 2018). Phthalates are known endocrine disruptors and have been associated with reproductive concerns, such as a decreased fecundity, pregnancy loss, and other adverse childbirth-related outcomes (Grindler et al. 2018). Given the high percentage of these additives in plastic and the potential environmental and human health effects, the leaching of these compounds from plastic roads remains an important knowledge gap.

Runoff from conventional roads contains contaminants with known toxicological effects, like metals and polycyclic aromatic hydrocarbons, as well as organic contaminants that are not yet identified and contain currently unknown environmental impacts. Tire wear particle leachate and roadway runoff has been linked to Coho salmon mortality (McIntyre et al. 2021) and developmental toxicity for fathead minnows (Chibwe et al. 2021). Conventional road runoff and tire/road wear particles have toxicity issues. The toxicity of road runoff and tire/road wear particles has not yet been studied to our knowledge. Further research should ensure that the use of plastic waste in road construction does not result in environmental health issues, such as aquatic and/or terrestrial toxicity.

The generation of hazardous chlorine gases during the process of road construction was noted by Sasidharan, Torbaghan, and Burrow (2019). This study found that bitumen alone generated harmful fumes, toluene, benzene, and aliphatic, cyclic, and aromatic hydrocarbons (White 2019).

Microplastic Generation

A knowledge gap exists regarding the amount of microplastics generated from plastic roads and their toxicity, in comparison to conventional roads. The company Neo and the National Center for Asphalt Technology separately reported that their institutions are undertaking research efforts to answer this question. We report below the generation of microplastics and future projections from conventional road traffic emissions.

When vehicle tires mechanically abrade conventional road surfaces, both tire and brake wear particles are generated, creating microplastics[16] and nanoplastics[17] (Evangeliou et al. 2020; Leads and Weinstein 2019; Sommer et al. 2018). There are three broad categories of road traffic emissions generated by vehicles and roads: tire wear particles, brake wear particles, and road sources (for example, polymer-modified bitumen, road marking paint) (Evangeliou et al. 2020).[18] Road traffic emissions exclude exhaust particles (Sommer et al. 2018). Based on the driving speed, traffic flow, and compo-

16 Plastics less than 5 mm in size (Arthur, Baker, and Bamford 2009).

17 Plastics less than 100 nm in size (Jahnke et al. 2017).

18 These three groups are sometimes all grouped together under the term 'tire wear particles'.

sition of the traffic, particles vary in size, composition, and structure (Sommer et al. 2018). When these particles are generated, they accumulate on the road and can be carried to the surrounding environment by wind, passing traffic, runoff, and can be dispersed into the atmosphere (Brahney et al. 2021; Evangeliou et al. 2020; Leads and Weinstein 2019; Sommer et al. 2018).

A recent study found that road and brakes generated 84 percent of microplastic emissions to the atmosphere in the Western United States (Brahney et al. 2021). Evangeliou et al. (2020) conducted similar global estimates of the amount of microplastics generated from tire and brake wear. In Asia, tire and brake wear generated 4.8–167 and 26–67 kilotons of annual road microplastic emissions, respectively (Evangeliou et al. 2020). A breakdown of the microplastic emissions quantified by size and a summary of the methods used is in **Annex H**.

Overall, the studies suggests that microplastic emissions from tires, breaks, and road wear generate a great amount of the microplastics that end up in the environment. Modeling by Lau et al. (2020) found that by 2040, tire particles are expected to contribute 93 percent of global microplastic pollution (by mass), even with coordinated, drastic global efforts to reduce plastic pollution. These studies are primarily representing conventional roads because the use of plastic waste in road construction is not yet commonly used except for roads in India.

Recyclability

It remains unknown whether plastic roads can be recycled at the end of life. Some companies have claimed that it is possible; however, this has not yet been established in the scientific literature to our knowledge (Willis, Yin, and Moraes 2020). Conventional asphalt pavement is highly recyclable; for example, pavements were recycled at a rate of over 99 percent in the United States in 2012 (Williams et al. 2018). However, in India, asphalt pavements are not removed or recycled on more than 70 percent of roads.

Regulatory and policy landscape: examples from India

Governments worldwide are adopting policies to reduce plastic pollution.[19] We identified the following policies adopted in India as calling for the use of plastic waste in road construction as a part of a mandate to reduce plastic pollution. Despite these regulations, plastic is not always incorporated into roads.

1. **Ministry of Environment, Forest, and Climate Change Notification.** Adopted in 2016 at the national level in India, this policy notes that *"local bodies shall encourage the use of plastic waste (preferably the plastic waste which cannot be further recycled) for road construction as per Indian Road Congress guidelines or energy recovery or waste to oil etc. The standards and pollution control norms specified by the prescribed authority for these technologies shall be complied with."*

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19 A review of broader plastic pollution reduction policies is outside of the scope of this report. For a detailed analysis of the global plastics policy landscape, please see Diana et al. (2022); Jambeck et al. (2018); Karasik et al. (2020); Schnurr et al. (2018); Xanthos and Walker (2017).

2. **Plastic Waste Management (Amendment) Rules, 2018.** Adopted in 2018 at the subnational level in Punjab, India, this amendment also notes that plastic waste should be used in road construction using the same policy instruments as the 2016 national-level 'Ministry of Environment, Forest, and Climate Change Notification'.

3. **Policy Circular no. 18.36/2019 (Amendment to use of waste plastic in hot bituminous mixes in IRC:SP: 98-2018).** Adopted in 2020, the National Highway Authority of India (NHAI) notes that "Bituminous Mix in the plastic waste will be the default mode of construction in wearing course of all service roads to be constructed by NHAI in all future projects."

The Ministry of Housing and Urba**n Affairs of the Government of India has encouraged the construction of roads using plastic waste in the Plastic Waste Management advisory report issued in March 2019. Additionally, the Government of India has recently announced the 'Plastic Waste Management (Amendment) Rules, 2022', which aim to extended producer responsibility regarding plastic packaging, promote a circular plastics economy, and develop alternatives to plastics (PTI 2022).** The Government of India's Ministry of Road Transport and Highways mandates the periodic renewal of roads within 50 kilometer of urban areas with over 5 lakh (=500,000) people, including at least 10 kilometer stretches of pilots using plastic waste in road construction in every state in India. Additionally, the Ministry of Rural Development has called for rural connectivity in the Pradhan Mantri Gram Sadak Yojana nationwide plan. KPMG (2021) notes that the government has encouraged the use of plastic waste in road construction without incentives and that the required approvals take over 60 days to begin a project.

India appears to have the greatest concentration and experience using plastic waste in road construction (Sasidharan, Torbaghan, and Burrow 2019). **To our knowledge, the 'Guidelines for the Use of Waste Plastic in Hot Bituminous Mixes (Dry Process) in Wearing Course' by the Indian Roads Congress (IRC: SP 98-2013) is the only standard that currently exists.** India is also home to road research institutions that study the use of plastic waste in road construction, such as the CSIR (New Delhi, India), and the KHRI. These institutes as well as many others contribute to India's expertise in the use of plastic waste in road construction.

The United Kingdom has started to create guidance on the use of plastic waste in road construction. In 2019, the United Kingdom government announced a £23 million investment into pilot projects using plastic waste in road construction in eight locales (Sasidharan, Torbaghan, and Burrow 2019).[20] This investment also aims to create guidance documents and specifications on the use of plastic waste in road construction (Sasidharan, Torbaghan, and Burrow 2019).

20 Buckinghamshire, Bedfordshire, Cumbria, Staffordshire, Kent, Reading, Suffolk, Solihull, and Birmingham

Engineering performance

It is important to study the engineering performance of plastic roads to ensure that roads remain intact and safe for various traffic volumes over time and throughout a range of climatic conditions. Bitumen modified with virgin polymers often increase fatigue cracking and rutting resistance (but not necessarily cracking resistance) (Fernandes, Silva, and Oliveira 2019). In general, bitumen modified with plastic waste is thought to behave similarly (Fernandes, Silva, and Oliveira 2019). Since the use of plastic waste in road construction is a relatively new idea that emerged within the last few decades, most of the engineering performance data that is known is from the laboratory instead of the field (Sasidharan, Torbaghan, and Burrow 2019).

Two broad categories of laboratory tests are conducted to verify that roads are engineered properly: (1) the laboratory binder characterization and (2) laboratory mixture characterization. As the name implies, laboratory binder characterization evaluates asphalt binder without the aggregate while the laboratory mixture characterization evaluates both the asphalt binder and the aggregate. Laboratory binder and mixture characterization tests have been developed for conventional asphalt pavement without the use of recycled plastic waste. However, researchers have begun to apply these tests to plastic roads though evidence on whether these tests are fully applicable to plastic roads is lacking (Willis, Yin, and Moraes 2020).

Enhanced rutting resistance has been noted in laboratory studies evaluating plastic waste modified bitumen (Table 4). **Enhancing rutting resistance often decreases cracking resistance.** Background on laboratory binder characterization and laboratory mixture characterization is provided in **Annexes I** and **J**.

Regarding the laboratory binder characterization (Willis, Yin, and Moraes 2020) the following key gaps on binder containing recycled plastics must be noted:

- Phase separation mitigation,
- Fatigue and cracking resistance,
- Applicability of standard asphalt binder tests,
- Compatibility with additives, and
- Need for new solvent and testing technologies.

There are also further key gaps to be addressed:

- Impact of use of plastic waste on highways with heavy pavements and high traffic loads,
- Impact of use of plastic waste in various types of asphalt layers under a range of environmental conditions,
- Methods to prevent leaching by design of appropriate cross-sections,
- Development of standard tests to assess leaching, and
- Long-term monitoring by research teams.

Further research in laboratory mixture characterization was noted by (Willis, Yin, and Moraes 2020) in the following areas:

- Fatigue and cracking resistance, especially of long-term aged samples, since existing studies expect plastic roads to have better rutting resistance which often has tradeoffs related to fatigue and cracking resistance;
- Quantification of structural design benefits to verify studies that show that the asphalt thickness could decrease due to increased mixture stiffness; and
- When using the dry process, researchers have not yet quantified if the plastic waste is evenly dispersed throughout the asphalt mixture.

Table 4.

Results of sample engineering performance studies.

Material studied	Primary findings or reports	Source
HDPE and LDPE modified bitumen	12% HDPE (by weight of bitumen) increases mixture stability, reduces mixture density, and slightly increases air voids and voids in mineral aggregate	Review by Aziz et al. (2015)
Plastic waste[21] modified bitumen	Increased the bitumen melting point, flexibility, rainwater tolerance, UV resistance, longevity, stiffness	Review by Gopinath et al. (2020)
HDPE modified bitumen	4–6% and 8% by weight of bitumen increased in Marshall stability, Marshall quotient, flow, resistance to permanent deformation	Review by Rahman, Mohajerani, and Giustozzi (2020)
Linear LDPE modified bitumen	3–6% by weight of bitumen increased the viscosity, softening point, and penetration index; decreased penetration value; improved elasticity (resistance against permanent deformation at high temperatures)	Nizamuddin et al. (2020)
Plastic waste in road construction	5–10% by weight of bitumen improves pavement stability, strength, and fatigue life as well as resistance to deformation and water damage	Review by Sasidharan, Torbaghan, and Burrow (2019)

21 Gopinath et al. (2020) also discuss PVC, HDPE, PET, and PE, but for the sake of brevity, just plastic waste broadly is presented in the table.

Economic analysis

Our analysis found at least five scientific articles and one report prepared for the World Bank reporting on the costs of plastic roads; only four of these provided cost figures. We added to the literature on the costs of plastic roads by conducting a CEA of plastic roads and found that plastic roads are economically justifiable (Annex K). All of the scientific articles in our sample of the peer-reviewed literature that reported on costs estimated cost savings (Khurshid et al. 2013; Lastra-Gonzalez et al. 2021). The KPMG (2021) report prepared for the World Bank found that plastic waste in road construction increased costs by US$0.14 per square meter of road, compared to conventional roads. This result was also found by the Government of India's Ministry of Railways (2019). Gopinath et al. (2020) summarized that plastic waste in road construction saved US$539.07 per kilometer of road, though further details are not provided. Krishnamoorthy et al. (2016) did not analyze costs but did report cost savings as a motivation for studying the engineering performance of tire rubber and polypropylene bottles in concrete material for road construction.

Two studies analyzed the cost of using recycled plastic waste, primarily polyethylene,[22] in road construction. The size of the road was similar in both studies.[23] The cost of plastic waste used for road construction and materials/processes related to the rest of plastic road construction can be found in Table 5 and 6. For consistency, the original values were calculated from their original currency (Indian Rupees for Khurshid et al. 2013 and Euros for Lastra-Gonzalez et al. 2021) to United States dollars (US$).[24]

22 The specific plastic types studied include HDPE from plastic bottles (8 percent of bitumen), PE obtained from copper cables (Pe-Cu) (25 percent weight of bitumen), and flexible PE packaging from the yellow container (film) (25 percent weight of bitumen) (Khurshid et al. 2013; Lastra-Gonzalez et al. 2021).

23 About 3.7 m in width and 1 km in length in Khurshid et al. (2013) and 3.5 m in width by 1 km in length in Lastra-Gonzalez et al. (2021). Lastra-Gonzalez et al. (2021) also specified the thickness of the road: a wearing layer (4 cm), binder layer (10 cm), and base layer (10 cm).

24 This currency equivalent calculation was made on June 8, 2021 using a currency equivalency calculator by Morningstar for Currency and Coinbase for Cryptocurrency.

Table 5.
Plastic waste costs for plastic road construction.

Plastic waste	Costs (US$/ton)	Included in cost	Source	Scientific paper associated
HDPE from plastic bottles	499	Plastic waste processing, collection, cleaning, and shredding costs	Estimated by surveying agencies involved in recycling and municipal waste management in India	Khurshid et al. 2013
PE from copper cables	49	Agency costs during material construction, maintenance, and end-of-life stages	Provided by source	Lastra-Gonzalez et al. 2021
Flexible PE packaging from the yellow container	365	Agency costs during material construction, maintenance, and end-of-life stages	Estimated	Lastra-Gonzalez et al. 2021
Polystyrene waste	477–656	Cost range depends on the processes needed[25]	Provided by a local company in Spain in the year 2015	(Vila-Cortavitarte et al. 2018)

Table 6.
Cost of non-plastic materials and related processes for plastic road construction.

Material/process	Costs (US$/ton)	Source
Plastic shredding plant	13,333.33-20,000[26]	KPMG 2021
Bitumen	536–547	de Fomento 2016 in Lastra-Gonzalez et al. 2021; Vila-Cortavitarte et al. 2018
	670	Sasidharan, Torbaghan, and Burrow 2019
Limestone aggregate	8–9	Lastra-Gonzalez et al. 2021; Vila-Cortavitarte et al. 2018
Ophitic aggregates	19–23	
Filler	50	CYPE Ingenieros 2019 in Lastra-Gonzalez et al. 2021
Construction	6	
Milling	36	
Transportation	US$0.12/(ton*km)	

25 Plastic that is lacking impurities only needs to be mechanically ground and will be on the lower end of the cost range. Other plastics that need to have impurities removed as well as use of a pelletizing machine to create smaller particles will have a higher cost. In this scenario, plastic is heated and then passed through a hole to create strands that are cut into smaller sizes (Villa-Cortavitarte et al. 2018).

26 Excludes land costs. Approximately 1–1.5 acres would be needed.

Plastic shredding centers can generate an additional revenue of Indian Rupee 6 per kg of otherwise non-recyclable plastics used in road construction, creating an additional income of Indian Rupees 1,500–2,000 per month per sanitary worker at the center (KPMG 2021). Employment benefits for waste pickers and entrepreneurs may be seen (KPMG 2021).

Khurshid et al. (2013) calculated that about US$1,936.49 would be saved per kilometer of road lane using HDPE in road construction at 8 percent by weight of bitumen,[27] in comparison to conventional road construction. Lastra-Gonzalez et al. (2021) conducted a life cycle cost analysis and found that certain plastic waste types used in road construction had cost savings when the durability of the plastic road mixture does not decrease below a certain amount (in the case 6.3 percent). Estimates by Lastra-Gonzalez et al. (2021) consider the service life of the road through traffic modeling and simulation using the software packages Alize and 3-4 Move (Lastra-Gonzalez et al. 2021). This simulation assumed only cracking (fatigue failure) would occur since Lastra-Gonzalez et al. (2021) found that rutting was unlikely given their laboratory test results. In the modeling simulation, a single axle dual tire[28] was used and an annual average daily traffic of 1400 vehicles with 2 percent traffic growth was simulated.

A report generated by KPMG for the World Bank assesses the scores of business models viability. In this

27 Unspecified whether rural or urban.

28 The assumptions behind the tire are that the tire has pressure of 900 kPa, load of 32 KN, radius of 0.106 m and center-to-center tire spacing of 0.3192 m (Lastra-Gonzalez et al. 2021).

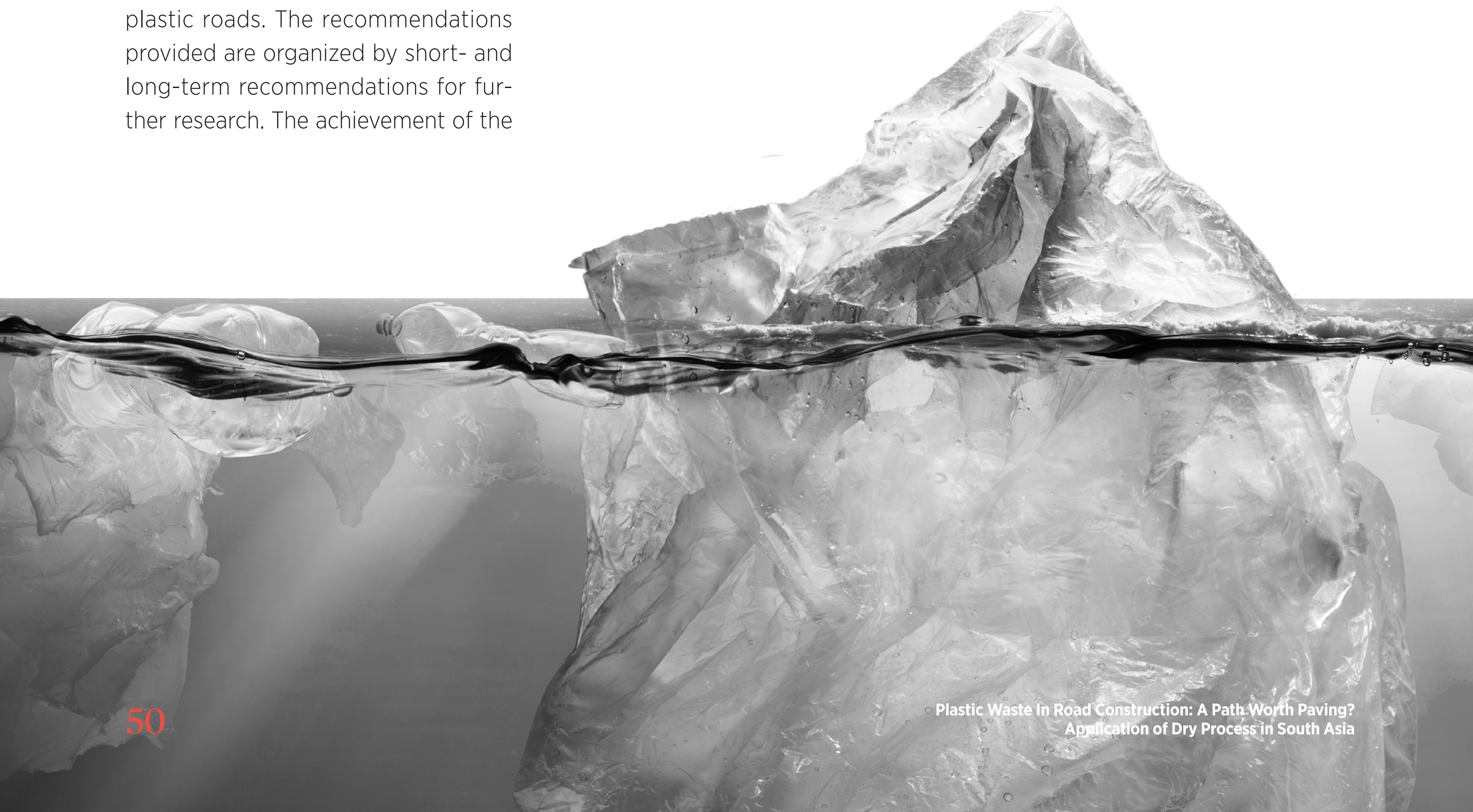
report, KPMG conducted a material flow analysis and cost-benefit analysis to determine the scalability of plastic waste business models at various sites[29] in India. The business models evaluated were plastic road construction, solid liquid resource management (SLRM), Areca palm sheaths as plastic cutlery alternatives, co-processing in cement kiln (plastic to fuel), and PET bottles to textiles (KPMG 2021). This analysis found that plastic road construction (bitumen modification) increased the cost of roads by US$0.14 per square meter of road (KPMG 2021), as was also found by the Government of India's Ministry of Railways (2019), in contrast to the scientific articles. The top business models according to KPMG (2021) is Areca palm sheaths as plastic cutlery alternatives, followed by SLRM. Plastic roads and co-processing in cement kilns had equal scores and followed SLRM. PET bottles to textiles had the lowest score. Despite plastic roads not receiving the top score, KPMG (2021) recommends partnering with local governments and the informal waste sector to promote this business model due to increased road performance, such as better resistance to water as well as widespread acceptance and government support in India.

Few studies have analyzed the cost to use plastic waste in road construction. This knowledge gap may reflect the idea that since bitumen is a by-product of crude petroleum (Vasudevan et al. 2012), which has generally increased in price over time (Aziz et al. 2015), partially substituting bitumen with plastic waste, which is plentiful, will save costs upfront. However, given that the incorporation of plastic waste can have a ripple effects in terms of cost, further cost-benefit or other economic analyses considering all the risk factors are greatly needed. Examples of additional costs include the price of new manufacturing and storage equipment and processes and changes in long-term upkeep. Economic analyses, such as a cost-benefit analysis, on the costs to construct a plastic road in comparison to a conventional road, appears to be a knowledge gap that would help to advance an evidence-based agenda for plastic roads.

29 These sites include Pulicat Lake, Gulf of Khambhat, and Vembanad Lake, spread across the states of Gujarat, Kerala, Tamil Nadu, and Andhra Pradesh (KPMG 2021).

6 Way Forward

We suggest that further research is needed to fill major gaps in our knowledge base of plastic roads. Opportunities for close monitoring and further research may be found in countries that are already piloting or using plastic roads. The recommendations provided are organized by short- and long-term recommendations for further research. The achievement of the short-term recommendations will provide necessary prerequisites and input into if and how the long-term recommendations should be pursued. These recommendations are specific to the use of plastic waste in road construction using the dry process, but we also recommend that researchers investigate alternative applications and treatment methods of plastic waste.



Short-term research

We recommend that short-term research be conducted before moving on to long-term research. Based on the short-term research results, interested stakeholders should determine if long-term research should be conducted or if resources should be allocated elsewhere. We recommend that an interdisciplinary team of experts in plastic waste applications, environmental and occupation health, and pavement technology spanning private entities, public-private partnerships, and governments conduct further research to fill the following gaps:

1. **Technology feasibility:** A gap exists regarding the quality assurance and control of the use of plastic waste in road construction. It is not known if plastic roads increase road cracking compared to conventional roads. Further studies should inform engineering performance and include the following parameters: "unevenness, skid number, texture (depth), field density, rebound deflection, and surface condition survey through tracking of the number of potholes, cracking, deformation and edge flaws" (KPMG 2021).

2. **Environmental issues:** We have highlighted three topics with research gaps that will inform the environmental sustainability of this technology: microplastics, additive leaching, and recyclability at the end of life.

- **(2a) Microplastics:** Although conventional roads and tire wear are known contributors to global microplastic pollution, we could not identify a study regarding the generation of microplastics and nanoplastics, specifically from plastic roads and tire wear. Microplastics generated from tire and plastic road wear should be a part of the ongoing plastic roads research agenda.
- **(2b) Additive leaching:** Additives leach out of plastics since they are not molecularly bonded to the polymer. Researchers should evaluate additive leaching from plastic waste used in roads. We did not identify studies quantifying the leaching of organic additives from plastic roads. Multiple interviewees reported forthcoming studies. We identified two studies on the leaching of metallic additives from plastic roads. Further research should be conducted on organic and inorganic additive leaching from roads, including how different plastic waste melting temperatures and road construction methods may or may not affect the leaching of plastic additives.
- **(2c) Recyclability at the end of life:** Research on the recyclability of plastic roads at the end of life is greatly needed. It is not known whether the plastic waste in roads or the entire plastic road can be recycled. Conventional asphalt pavements are highly recyclable so care should be taken to make the plastic roads as recyclable as the conventional roads. If plastic roads cannot be recycled, further environmental considerations will be needed around the potential burying of plastic in layers of road over time. The following factors should also be considered: the adhesion of asphalt to plastic which can complicate recycling and the disposal of materials generated during road construction and repairs.

Long-term research

If the aforementioned research gaps are filled, we recommend that interested stakeholders conduct further long-term applied research in a field setting and/or through conducting pilot projects. We expect that a stocktaking of performance monitoring results from existing plastic roads pilot projects will be helpful. Field research and pilot projects should only be pursued if the results of the short-term research suggest that plastic roads are a viable option that is protective of environmental and human health.

If supported by the short-term research, we recommend conducting long-term research and pilot projects to fill the following gaps:

1. **Technology feasibility:** Field simulated research studies and pilot projects will aid in accelerating the scientific understanding of long-term plastic road performance. These studies should be conducted under a range of environmental conditions, including under flooding conditions, sunlight, high-pressure, and extreme events, such as fires, chemical spills, and other environmental accidents or natural disasters. These long-term studies should determine road moisture susceptibility, road wear, filtrate management, and engineering performance, including factors such as rutting, cracking resistance, progression of deflection and roughness, and oxidation.

   Further research is needed to determine the scalability of this technology. In partnership with bitumen suppliers, interested stakeholders should determine if plastic waste can be used in base and subbase courses of pavements to increase the percentage of plastic waste used. Furthermore, interested stakeholders should evaluate the quality of plastic supply, plastic waste capture, and regional plastic waste collection rates to evaluate if plastic roads can be scaled up in a given geographic area. Long-term performance studies should also inform the scalability of this technology.

2. **Environmental:** Further research is needed on the benefits and downsides of plastic roads, as compared to conventional roads, from a life cycle perspective. Most of the life cycle analyses identified in this study were conducted on plastic roads in high-income countries. We suggest that further research evaluate plastic roads from a life cycle perspective, including greenhouse gas emissions, in lower-income settings.

3. **Occupational health:** Further occupational health guidelines and trainings are needed. Fires may occur if recycled plastics contact the burner flame or clog the filter bags at the asphalt plant (Willis, Yin, and Moraes 2020). Heating of plastic waste can generate hazardous air pollutants, such as volatile organic compounds (Willis, Yin, and Moraes 2020). We expect that guidelines can be developed to protect occupational health from generating and inhaling hazardous air pollutants. Interviews and partnerships with equipment manufacturers will allow operational retrofits at the plant to be researched and costs to be estimated. Interested stakeholders should consider generating occupational health guidelines.

4. **Economic viability:** Cost-benefit analyses that compare plastic roads to conventional roads should be conducted to sharpen current findings. The CEA conducted as a part of this study and reports in the scientific literature generally report cost savings. However, cost-benefit analyses by KPMG and results from the Government of India's Ministry of Railways (2019) indicated that plastic roads are $0.14 USD per square meter of the road more expensive than conventional roads (KPMG, 2021). Detailed cost-benefit analyses that are ground-truthed with data from the field, including the life span of plastic roads, will help sort out conflicting reports.

5. **Industry standards:** We recommend that industry standards be developed to ensure the asphalt mix's consistency. Industry standards should specify the amount and types of asphalt and plastic waste incorporated into plastic roads. Standardized tests should be developed to ensure the proper inputs and methods are used to construct plastic roads.

   Since plastic additives range and can include over 10,000 ad-

ditives, at least 2,400 of which have known toxicological issues (Wiesinger, Wang, and Hellweg 2021), further work should be conducted to standardize the additives used in plastics. Standardizing plastic additives will aid in researchers' understanding of the quantities and chemical compounds that are leaching. Advancements in the standardization of additives in plastic will aid in using plastic waste as an input into plastic roads and other materials.

Ultimately, plastic production and subsequent waste generation need to be reduced via a 'full life cycle approach' as noted in the upcoming international legally-binding treaty to reduce plastic pollution. The use of plastic waste in road construction is an emerging approach to utilize plastic waste as a partial substitute for bitumen. This new technology is a downstream measure, addressing plastic pollution after it has already become waste. Upstream measures that slow the generation of plastic production and subsequent waste are greatly needed.

Through both upstream and downstream measures, a 'full life cycle approach' to reduce plastic pollution can be realized.

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Annex A.

Methods

We met with Duke University and World Bank librarians to craft search strings that will help us to answer the following research questions:

- **a.** What is plastic waste-to-road technology?
- **b.** What are the environmental and economic benefits and downsides of implementing plastic roads?
- **c.** Who are the major companies implementing plastic roads and where have plastic roads been implemented?
- **d.** What is the regulatory landscape surrounding plastic roads?

We reviewed the business news databases, Abstracted Business Information (ABI) Inform and Dow Jones Factiva, to find out where plastic roads have been implemented and by whom. We used the search strings in Table 7 to extract relevant articles in each database. The databases have different search functions, so the search strings were adjusted for each database. In the ABI Inform search string,"su (road)" indicated that the subject of the article is the road. In Dow Jones Factiva, "w/3" only returned results that have the search terms within three words of one another.

Table 7.
Search strings used to identify those who are building plastic roads and geographic locations constructed or planned plastic roads

Databases	Search strings	Number of returns
ABI Inform	su (road) AND recycled AND plastic AND project	318
Dow Jones Factiva	(plastic or polyethylene or polymer) w/3 (road or pavement or asphalt or bitum*) and (waste OR recycl*)	181
World Bank Group Library	((environment* sustainabil* AND plastic) OR microplastic* OR (fumes NEAR5 leach) OR plastic) AND (road OR pavement OR bitum* OR highway OR thoroughfare)	102

Article cutoffs were established before reviewing the articles. We stopped reviewing articles after 20 consecutive articles were irrelevant or after 20 percent of returns were reviewed, whichever was reached first. For the World Bank Group Library, all results were reviewed because the librarian sent over only relevant searches.

News articles were reviewed to determine if the use of plastic waste or rubber tires in road construction was discussed or mentioned and if so, predetermined data points of interest were extracted. Articles were excluded if they did not mention recycling plastic into roads; specify that plastic waste or recycled plastic was used, as opposed to virgin polymer; and mention building roads from plastic waste, but just discussed plastic waste more broadly. We collected data on the type of article title, author, publisher, and date of publication. We identified relevant news articles based on the title of the article and full-text review. Articles were considered relevant if they discussed the construction or planned construction of a plastic road in as little as one sentence. We extracted data on points of interest, listed below, in relevant articles. For certain points of data, we used a numbered system to organize the data. Numbers were not used for statistical scoring.

The data points of interest fell into the following categories: geographic location of the road, construction status of the road at the time of news article publication, plastic road specifications, company constructing the road, key stakeholders, and economic/cost data. For each category of interest, we had predetermined data extraction points, which are detailed for each category in the following paragraphs.

For the geographic location(s) of the road(s), one researcher extracted the city and country of the plastic road. In some instances, only the country was specified. For each road described, one researcher also noted the status of the road at the time of article publication by selecting one of the following options:

- Constructed,
- Planned for future construction/pilot/under construction, or
- Planned for future construction but dropped.

If the road was already constructed, the year of the road construction was noted. If provided, the length of the already constructed road or the planned length of a plastic road to be constructed in the future was indicated in kilometers.

We characterized the type and amount of plastic used to construct plastic roads. One researcher selected one or more of the following types of plastic item(s) (if applicable): bags, bottles, and others—specified and unspecified. If the article characterized the plastic item or plastic waste used in road construction by recycling category, we selected one or more of the following recycling categories: PET (1), HDPE (2), PVC (3), LDPE (4), PP (5), PS (6), other (7), and/or unspecified (8). The amount of plastic (kg) and percentage substituted for bitumen or aggregate were noted.

We characterized key stakeholders by recording any company, government, or developmental organization affiliated with constructing and/or financing the plastic road. The name of the company constructing the road was recorded. The name of the government financing the road (if applicable), the amount financed (US$), and the name of other relevant partners were noted. Lastly, the name of the developmental organization, the amount financed (US$), and the name of other relevant partners were noted.

Regarding economic and costs data, we recorded if a cost-benefit analysis was conducted and collected other costs that were reported. We also shared any costs reported with regard to building plastic roads in either US dollars per ton of road, US dollars per ton of plastic, or US dollars per km of road, depending on what was reported in the news article. If the cost of a conventional road (no plastic waste incorporated) was discussed, we recorded the road construction materials described and cost in US dollars per ton of road and/or US dollars per km of road. Any alternative mode of plastic waste management (for example, incineration) was noted and associated costs (US dollar per ton of plastic) were noted.

To identify businesses that construct plastic roads, one researcher searched brief company descriptions (about a paragraph long) returned by keywords (Table 8) searched in the S&P Capital IQ business database. One researcher reviewed the returned company descriptions to determine the company's relevancy to plastic roads (n=141 company descriptions). Companies that appeared to be a part of the plastic roads industry were added to a separate database (n=9 companies). Duplicate companies were not added. If it was unclear whether a company was a plastic roads company (for example, companies that construct roads using virgin plastics), company websites were identified, if possible, and the company's product catalog, sustainability report, and broader descriptions were reviewed to determine if plastic waste is used in road construction.

Table 8.
Keywords queried in brief business descriptions in Standard and Poor's (S&P) Capital IQ

Keywords searched in S&P Capital IQ
Plastic highway
Plastic pave
Plastic road
Plastic recycle roads
Plastic waste roads

Plastic roads businesses were compiled. Contact information for representatives ranging from engineers to founders to public relations contacts were collected and one individual per company was contacted for an interview lasting no longer than on hour. The goal of the interviews was to ground-truth our findings from news articles and the scientific literature. Interview questions are shared below.

Interview questions

By 'plastic roads' or 'plastic waste-to-road technology', we are referring to the use of recycled plastic or plastic waste in the construction of vehicular roads, bicycle paths, or pedestrian walkways.

Technology

Please describe plastic waste-to-road technology.

a. Which other primary material does plastic substitute for in road construction?
b. Which plastic recycling categories are primarily used to construct plastic roads?
c. What percentage(s) of the road comprises plastic waste and in which geographic location(s)?
d. Where do you source your plastic waste from? Are you aware of what would have happened to the plastic waste had it not been used in road construction?
e. Are plastic roads socially accepted or alternatively, do plastic roads cause stress?

Environmental and economic sustainability

Please describe the environmental benefits and harms from plastic waste-to-road technology.

a. What are the greatest environmental benefits brought on by the construction of plastic roads?
   - If so, are these environmental benefits realized by all types of plastic roads or only those comprising certain plastic recycling types/compositions? How do these benefits compare to traditional road construction or other waste management alternatives?
   - If so, have you measured or otherwise witnessed these environmental benefits in projects implemented by your company or others?
b. What are the greatest environmental harms or externalities posed by plastic roads?
   - If so, are these environmental harms brought on by all types of plastic roads or only those comprising certain plastic recycling types/compositions? How do these harms compare to traditional road construction or other waste management alternatives?
   - If so, have you measured or otherwise witnessed these environmental harms in projects implemented by your company or others?
c. What happens to plastic roads at the end of their life stages?
d. What is the cost (or range of costs) to construct plastic roads in comparison to traditional roads (lacking recycled polymer) or alternate plastic waste management schemes?
   - What factors may raise or lower the cost of constructing of plastic roads?
   - Have you or others conducted a cost-benefit analysis on the construction of plastic roads? If so, what were the results, or would you be willing to share the study with us?
e. What are the costs of upkeeping plastic roads over time? How do these costs compare to traditional road construction costs or alternatively, plastic waste management costs?

Stakeholders

Please describe the role of your business/employer in the larger industry to us.

a. How long has your company implemented plastic waste-to-road technology? Do you have an estimation of how many miles of plastic roads your company has installed?
b. Is your business responsible for the entire life cycle of plastic roads, such as procuring the plastic waste, processing it, and installing the road or one or more tasks in the process? Please describe your business's role in the process of constructing plastic roads.
c. Where (which country, no need to specify exact locations) does your business or your contractor construct plastic roads?
   - What is the existing legal framework for construction of plastic roads in that location?

- Does this legal framework hinder or support the construction of plastic roads?

d. Regarding the financing of private roads, have you worked with any major development organizations?
- If so, which organizations?
- If so, which geographic locations (country level)?

Notes were taken during interviews for recordkeeping and incorporation into the report. Depending on the interviewee(s) preference, some interviews were recorded for note-taking purposes only.

We conducted a search in Web of Science to find peer-reviewed articles that help us answer (1) what is plastic waste-to-road technology and (2) what are the environmental and economic benefits and downsides of implementing plastic roads. We searched the Boolean strings in Table 9 in Web of Science. These search strings were created iteratively by reviewing the title, keywords, abstract of scientific articles, and one piece of gray literature that appeared highly relevant to our search questions: (Aziz et al. 2015; Biswas, Goel, and Potnis 2020; Fernandes, Silva, and Oliveira 2019b; Gopinath et al. 2020; Limantara et al. 2018; Rahman, Mohajerani, and Giustozzi 2020; Sabzoi et al. 2020; Santos et al. 2021; Sasidharan, Torbaghan, and Burrow 2019; Vasudevan et al. 2012; White 2020).

Table 9.
Web of Science search string

Database	Boolean search strings	Number of returns
Web of Science	TITLE: (road* OR pavement* OR concrete OR asphalt OR bitum*) AND TOPIC: (polymer* OR plastic* OR polyethylene) AND TOPIC: (waste OR recycl* OR bottles OR "alternative materials") AND TOPIC: "toxic* OR gas* OR metal* OR chemical* OR deteriorate* OR distress OR leach* OR ecotoxicity OR health OR ozone OR "life cycle:)	520

Articles were sorted by relevance, and before reviewing, we developed cutoff criteria. We stopped reviewing when (1) either after 20 consecutive irrelevant articles (as determined by screening the abstract and title) or (2) after 20 percent of the articles were screened, whichever was reached first. Article titles and abstracts were reviewed for a reference to the use of plastic waste in roads and if present, the articles underwent full text screening. Scientific articles were excluded based on the same criteria used for news articles.

Each article was reviewed to determine if it was peer-reviewed, a review article, or other. We reviewed included articles to extract data on environmental and economic concerns and benefits noted below.

The environmental concerns reviewed within this report include the generation of noxious fumes, greenhouse gas emissions, microplastic leakage, and/or leaching of additives from or during the construction of plastic roads. For each of these categories, one researcher noted if the concern was discussed (or mentioned as little as in one line) or not. If the concern was noted, the amount and type of each pollutant was noted. For example, for fumes, the amount and types of fumes produced would be recorded. For microplastics, only the amount of microplastics produced would be noted. An 'other' category was created to note other environmental concerns and reported from plastic roads that did not fall into the previous categories.

We also summarized the following predetermined data points from studies that conduct LCA of plastic roads:

- Country of plastic road studied,
- Primary data (yes/no),
- LCA database used,
- Functional/declared unit,
- Plastic type(s),
- Wet/dry process of plastic road construction,
- Percentage of bitumen replaced,
- Impact assessment, and
- Impact categories.

These data points help us compare and contrast the LCA studies reviewed as a part of this study.

Engineering performance studies from Web of Science were reviewed to provide an overview of the types of plastic roads researched. Data were extracted on the following topics: the plastic waste type(s) being tested in asphalt mixtures; percentage substituted for bitumen; and the use of Marshall Stability, Superpave Performance Grading, or both Marshall Stability and Superpave Performance Grading. The specific plastic types that we used as categories were the following: PET, HDPE, PVC, LDPE, PP, PS, Other, and/or Unspecified.

To review plastic roads patents, one researcher searched the Boolean string "plastic waste AND (paving OR coated OR pavements OR asphalt)" in the World Intellectual Property Organization's Patentscope database. Before beginning the patent database search, we set a rule that the researcher would review the first 20 percent of patents or stop reviewing when the researcher came across 20 consecutive irrelevant results. Upon reviewing the patent abstract and description, one researcher extracted the following data on any patents that incorporated waste or recycled plastic into road construction material:

- Patent filing date,
- Patent publication date,
- Inventor,
- Applicant,
- Post-consumer or postindustrial plastic waste (if specified),
- Plastic type (if specified),
  - PET - 1
  - HDPE - 2
  - PVC - 3
  - LDPE - 4
  - PP - 5
  - PS - 6
  - PU
  - Crumb rubber/rubber/tires
  - Other - 7
  - Unspecified - 8
- Percentage of bitumen comprising plastic (if specified), and
- Hyperlink to the original patent in the Patentscope database.

Using the free, open-access database of policies adopted to reduce plastic pollution in Karasik et al. (2020) and Diana et al. (2022) (that is, the Plastic Policy Inventory), we searched the terms "road" and "pavement" to find policies adopted that encouraged the use of plastic waste in road construction. Original policy documents were reviewed by one researcher to determine if the sections describing plastic pollution reduction efforts referred to the use of plastic waste in road construction. The analysis by Karasik et al. (2020) and Diana et al. (2022) has an English language bias and is not representative of the global plastics policy landscape at the national and subnational levels so additional policies may exist.

Annex B.

Plastic waste

An overview of plastic recycling categories can be found in Table 10.

Table 10.
Plastic recycling categories

Recycling category	Plastics type	Application/Uses	Melting Point (°C) [1]
1	Polyethylene Terephalate (PET)	Bottles for water and soda, food packaging, food containers	>250
2	High Density Polyethylene (HDPE)	Plastic mailing envelopes, flexible pipes, plastic chairs/stools, toys and playground equipment, plastic bags shampoo bottles	130 but can vary in grade
3	Polyvinyl Chloride (PVC)	Pipes, electric cables, construction material, sign boards, vinyl flooring	100–260
4	Low Density Polyethylene (LDPE)	Trays and containers, plastic wraps, plastic bags, juice, and milk containers	110–120
5	Polypropylene (PP)	Plastic hinges, piping system, plastic chairs, reusable plastic containers, plastic moldings	160–165
6	Polystyrene (PS)	Food packaging, CD and DVD casing, disposable utensils, license plate frames, foam beverage cups	Glass transition at 100
7	Other[2]	Baby bottles, car parts, water cooler bottles, food containers	Based on grade and plastic type

Source: Willis, Yin, and Moraes 2020.

1 When using recycled plastic as mixture modifiers for the dry process, plastics with a low melting point (for example, Linear Low Denstiy Polyethylene (LLDPE), LDPE, and HDPE) were reported to be beneficial because they coat hot aggregates upon mixing.

2 Other may include Polycarbonate (PC), Polylactide (PLCA), Acrylonitrile Butadiene Styrene (ABS), nylon, fiberglass, and acrylic (Willis, Yin, and Moraes 2020).

Table 11.
Sample of plastic additives

Plastic additive	% of additive in global additive production	Example substances
Plasticizers	34	Dibutyl phthalate
Flame retardants	13	Brominated flame retardants with antimony as synergist and phosphorous flame retardant
Stabilizers (including heat and UV) and anti-oxidants	12	Cadmium and lead compounds
Fillers	28	Metal powders, calcium carbonate, zinc oxide, and clay
Impact modifiers	5	Rubbers
Colorants/pigments	2	Azo-dyes, cadmium, chromium, and lead compounds
Lubricants	2	Silicone oils
Other (for example, biocides)	4	Arsenic compounds and organic tin compounds

Source: Ebnesajjad and Morgan 2019; Geyer, Jambeck, and Law 2017; Hahladakis et al. 2018; Pritchard 2012.

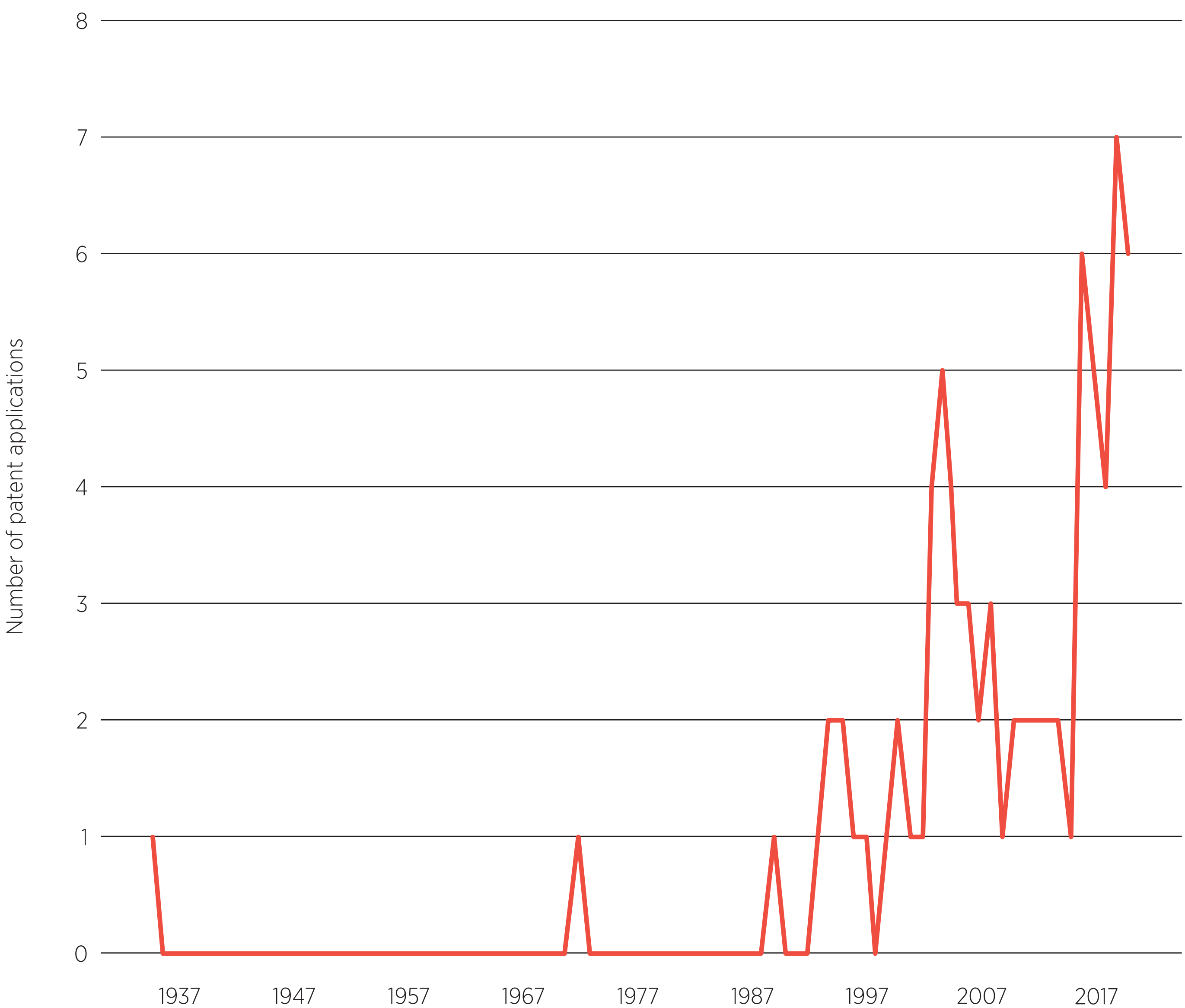
Plastic waste in road construction

We identified 76 patent applications and subsequent publications for inventions incorporating plastic or crumb rubber waste into plastic roads between 1935 and 2021. Over time, more companies and inventors applied for patents that incorporated the use of plastic and crumb rubber waste into road construction (Figure 6).

These patents reported using post-consumer and post-industrial waste in road construction. A total of 27 patents were filed used both post-consumer and post-industrial plastic waste. Both post-consumer and post-industrial waste were incorporated into road construction according to patents identified in the patent database. The specific plastic types included LDPE, HDPE, PET, PVC, PU, rubber tires, PP, PS, polyolefm, polyamide, Polyvinyl Butyral, styrene isoprene styrene, ethylene-vinyl acetate (EVA), ABS, polyesters, polyolefin waxes, PS butadiene rubber, and styrene butadiene rubber. A total of 19 patents that were filed used only post-consumer plastic waste for the following types of plastic: LDPE, HDPE, Polyethylene, PET, PP, PS, PVC, polyamide, acrylic, rubber tires, and other unspecified plastics. Six patents used only post-industrial plastic waste, specifically LDPE, HDPE, Polyethylene, PET, PVC, PP, ABS, polyamide, PC, polyoxomethylene, polyester, acrylic, and fiberglass reinforced plastic. One patent that used post-industrial waste reported using by-products of the plastic recycling and polymer processing process, such as cellulose product recycle industry waste, fibrous cellulose product processing industry waste, high molecular weight polymer industry effluents, effluent treatment plant sludge and natural and synthetic polymer processing waste, and related products. The remaining patents did not specify the type of plastic waste used.

Figure 6.

Number of patent applications in our sample filed annually (non-cumulative) from 1935 to 2021

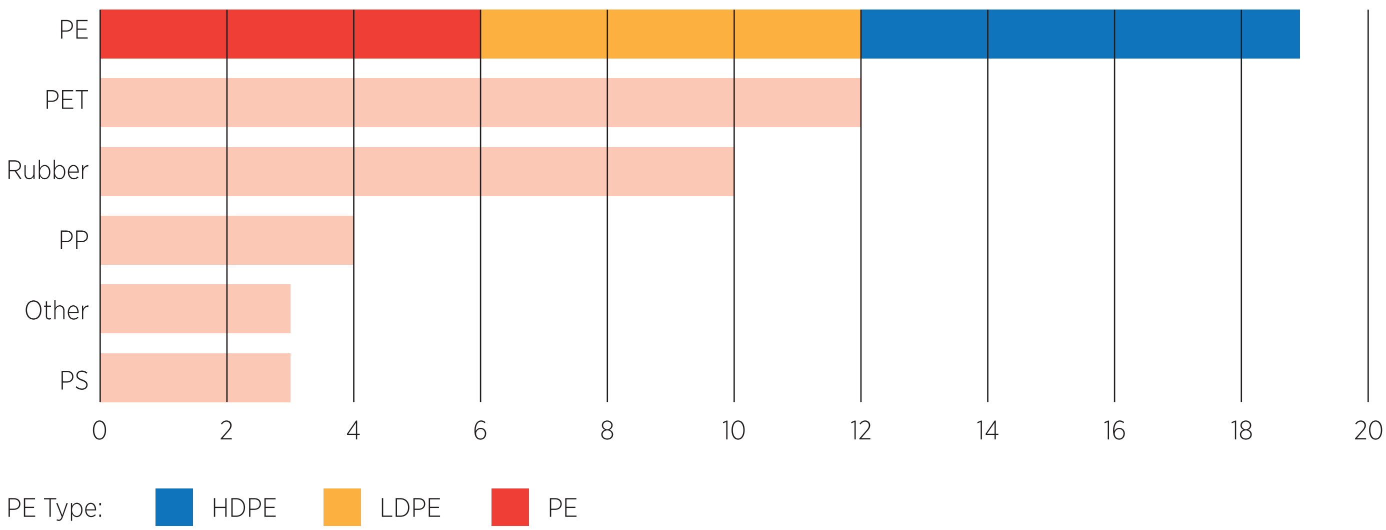


Note: Patents were retrieved from the World Intellectual Property Organization's Patentscope database using the methods described above.

Multiple plastic recycling categories can be used in plastic road construction. Willis, Yin, and Moraes (2020) found that the wet process was most frequently studied in the literature (n=57 documents), while the dry process was studied less commonly (n=35 documents). However, the dry process is used most in India where plastic roads are widespread and widely accepted (Biswas, Goel, and Potnis 2020; IRC 2013). A summary of scientific articles (excluding review articles) using each plastic type can be found in Figure 7. The 'Rubber' category primarily includes crumb rubber from waste tires, though one scientific article studies waste nitrile rubber from sole shoe milling. The 'Other' category includes cigarette butts comprising cellulose acetate and the top and bottom layers of unused single-use face masks procured during the 2019 novel coronavirus (COVID-19) pandemic, which has top and bottom layers made of non-woven fabric.

Figure 7.

Number of scientific articles in our sample studying each plastic type



These results are consistent with the review by Willis, Yin, and Moraes (2020) who found that various polyethylene plastics were studied most frequently followed by PET. Willis, Yin, and Moraes (2020) did not include rubber products in their study so PP was the next most common. Our search terms focused on the use of plastic waste (for example, 'polymer', 'plastic', and 'polyethylene') as opposed to tire waste, so we expect that we would find more articles on rubber or tires by altering the keywords used in the searches. We did not find any studies using PVC or PU, though Willis, Yin, and Moraes (2020) found 5 studies using PVC and 1 study using PU, respectively.

The range of percentages that plastic waste was studied in the scientific literature varies by plastic type, with a median range between 2 and 9 percent for plastic recycling categories and rubber. In Table 12, the range, median, and mean percentage of plastic waste substituted for bitumen is shown by plastic type.

Table 12.

Percentages of bitumen substituted by plastic waste

	Average (%)	Range (%)	Median (%)
PP	13	0 to 50	5
Rubber	11	0 to 50	9
HDPE	7	0 to 20	6
LDPE	6	2 to 15	5
Polyethylene	6	0.2 to 25	5
PET	4	0 to 30	2
PS	3	0 to 6	3
Other	1	0 to 3	0.4

Annex C.

Reports from news articles

The following tons of plastic per one kilometer of road were reported in news articles for roads that have already been constructed:

- 0.43 tons of plastic/1 km of road (1.7 tons/4.0 km) in Guanajuato, Mexico (Anonymous 2019)
- 0.12 tons of plastic/1 km of road (1.7 tons/14 km) in Guanajuato, Mexico (Alcántara 2019)
- 0.5 tons of plastic /1km of road (1 tons/2 km) in Guanajuato, Mexico (Anonymous 2019)
- 0.91 tons of plastic/1 km of road (41 tons/45 km) in Guwahati, India (Mitra 2019)
- 0.48 tons of plastic/1 km of road (2.4 tons/5 km) in Bareilly, Uttar Pradesh, India (Khan 2019)
- 1.3 tons of plastic/1 km of road (0.4 tons/0.3 km) of road in Kavi Nagar, India (Dev 2019)
- 2 tons of plastic/1 km of road (0.5 tons/0.25 km) in Pune, India (Anonymous 2018).

Annex D.

Sample of Indian Roads Congress standards (IRC: SP 98-2013)

> *“The waste plastic shall conform to the size passing 2.36 mm sieve and retained on 600 micron sieve.*
> *Dust and other impurities shall not be more than1 percent. The process is indicated in Appendix-2. An easy method to determine the quantity of impurity is to determine the ash content at 600°C.*
> *To ascertain the ability of plastic to mix with the binder, the melt-flow value shall be tested as per ASTM D 1238-2010, for which the range shall be as*
> *For LDPE: 0.14-58 gm/10 min*
> *For HDPE: 0.02-9.0 gm/10 min.”*

Annex E.

Relevant businesses

The geographic locations of the plastic roads that are (1) constructed, (2) planned for future construction, but dropped, or (3) planned, under construction, or undergoing a pilot project in Figure 4 are found below in Table 13.

Table 13.
Geographic locations of plastic roads

City	Country	Status of plastic road	Source
Hume	Australia	Planned, under construction, or undergoing a pilot project	(Real Estate Monitor Worldwide 2018)
Rayfield Avenue, Craigieburn	Australia	Constructed	(Anonymous 2018a)
Victoria	Australia	Planned, under construction, or undergoing a pilot project	(News Bites - Private Companies 2020a)
Shanghai	China	Constructed	(Yeo and Tan 2021)
Not specified	Estonia	Constructed	(The Times 2019)
Pons/Saint Aubin	France	Constructed	(Gorman 2018)
Ashaiman	Ghana	Planned, under construction, or undergoing a pilot project	(Sawer 2018)
Not specified	Holland	Constructed	(Noticias Financieras, 2020)
11 states (unnamed)	India	Constructed	(Khanna 2019)
Agra, Uttar Pradesh	India	Planned, under construction, or undergoing a pilot project	(Lavania 2019a; Lavania 2019b)
Ahmedabad	India	Constructed	(The Times of India 2019e)
Bangalore	India	Constructed	(The Times of India 2019e)
Bareilly, Uttar Pradesh	India	Planned, under construction, or undergoing a pilot project	(Khan 2019)
Bareilly, Uttar Pradesh	India	Constructed	(Khan 2019)

City	Country	Status of plastic road	Source
Bengaluru	India	Planned for future construction but dropped	(Chakravorty 2019)
Bengaluru	India	Planned, under construction, or undergoing a pilot project	(TNN, 2019; The Times of India 2019d)
City Centre II, Kolkata	India	Constructed	(Chakraborti 2020)
Doon, Dehradun	India	Planned, under construction, or undergoing a pilot project	(Jha 2019)
Doon, Dehradun	India	Planned for future construction but dropped	(Jha 2019)
Gurgaon	India	Planned, under construction, or undergoing a pilot project	(Chaman 2020)
Guwahati	India	Constructed	(Mitra 2019)
Jamshedpur	India	Planned, under construction, or undergoing a pilot project	(Chatterjee 2020)
Kavi Nagar	India	Constructed	(Dev 2019)
Kavi Nagar	India	Planned, under construction, or undergoing a pilot project	(Dev 2019)
Kazhakoottam-Muk-kola stretch, Thiruva-nanthapuram	India	Planned, under construction, or undergoing a pilot project	(Surya 2019)
Kochi	India	Planned, under construction, or undergoing a pilot project	(Nambudiri 2019)
Kohlapur	India	Planned, under construction, or undergoing a pilot project	(The Times of India 2019b)
Maharashtra	India	Planned, under construction, or undergoing a pilot project	(Real Estate Monitor Worldwide 2017)
Maharashtra	India	Constructed	(Dutta 2019)
Mukkola-Karode, Thi-ruvananthapuram	India	Planned, under construction, or undergoing a pilot project	(Surya 2019)
Mumbai	India	Planned for future construction but dropped	(Manju 2019)
New Delhi	India	Planned, under construction, or undergoing a pilot project	(Mathur 2009; Singh 2019)
New Town, Kolkata	India	Planned, under construction, or undergoing a pilot project	(Chakraborti 2020)
Noida	India	Planned, under construction, or undergoing a pilot project	(Singh 2019; The Times of India 2019c; The Times of India 2020)

City	Country	Status of plastic road	Source
Odisha	India	Planned, under construction, or undergoing a pilot project	(Mazumdar 2018; Ramanath 2019)
Palakkad	India	Planned, under construction, or undergoing a pilot project	(Surya 2019)
Pune	India	Planned, under construction, or undergoing a pilot project	(Popular Plastics and Packaging 2018)
Pune	India	Constructed	(Anonymous 2018c)
Sanjay Nagar	India	Planned, under construction, or undergoing a pilot project	(Dev 2019)
Thiruvananthapuram	India	Planned for future construction but dropped	(The Times of India 2019a; Surya 2019)
Thiruvananthapuram	India	Constructed	(The Times of India 2019a; The Times of India 2019f)
Thiruvananthapuram	India	Planned, under construction, or undergoing a pilot project	(The Times of India 2019f)
Uttar Pradesh	India	Planned, under construction, or undergoing a pilot project	(New Building Materials & Construction World, 2020; Shah 2020;)
Not specified	Indonesia	Planned, under construction, or undergoing a pilot project	(Anonymous 2017)
Not specified	Iran	Planned, under construction, or undergoing a pilot project	(BBC Monitoring Americas 2016)
Rome	Italy	Planned, under construction, or undergoing a pilot project	(Willan 2019)
Guanajuato	Mexico	Constructed	(Benzinga Newswires 2019; Alcántara 2019; Noticias Financieras 2019)
Guanajuato	Mexico	Planned, under construction, or undergoing a pilot project	(CE Noticias Financieras 2019; Rocha 2020)
Not specified	Mexico	Constructed	(Noticias Financieras 2020)
Zwolle	Netherlands	Planned, under construction, or undergoing a pilot project	(Kotecki 2018; Anonymous 2018a; Guardian 2015)
Rotterdam	Netherlands	Planned, under construction, or undergoing a pilot project	(Progressive Digital Media Packaging News 2015)
San Carlos, Chiriqui	Panama	Planned for future construction but dropped	(Noticias Financieras 2019b)
Arraiján	Panama	Planned for future construction but dropped	(Noticias Financieras 2019b)

City	Country	Status of plastic road	Source
Not specified	Philippines	Planned, under construction, or undergoing a pilot project	(Asia News Monitor 2019; Business Mirror 2019a)
Mandaluyong	Philippines	Planned, under construction, or undergoing a pilot project	(Asia News Monitor 2020)
General Trias, Cavite	Philippines	Planned, under construction, or undergoing a pilot project	(Business Mirror 2019b)
Springfield Properties, Elgin	Scotland	Planned, under construction, or undergoing a pilot project	(News Bites - Private Companies 2020b)
Kouga Municipality	South Africa	Planned, under construction, or undergoing a pilot project	(Real Estate Monitor Worldwide 2019a)
Jeffrey's Bay	South Africa	Planned, under construction, or undergoing a pilot project	(Fullerton 2019)
Not specified	South Africa	Constructed	(The Times 2019)
Durham	United Kingdom	Constructed	(Engelbrecht 2020)
Durham	United Kingdom	Planned, under construction, or undergoing a pilot project	(Engelbrecht 2020)
Not specified	United Kingdom	Planned, under construction, or undergoing a pilot project	(Rocha 2020)
Ollerton, Nottinghamshire	United Kingdom	Constructed	(News Bites - Private Companies 2020d)
Queen Elizabeth Olympic Park, Stratford, London	United Kingdom	Constructed	(News Bites - Private Companies 2019)
Wolverhampton	United Kingdom	Constructed	(News Bites - Private Companies 2020c)
Carlisle, Cumbria	United Kingdom	Planned, under construction, or undergoing a pilot project	(Real Estate Monitor Worldwide 2020)
Bangor, Maine	United States	Constructed	(Steuteville 1996)
Clare, New York	United States	Planned, under construction, or undergoing a pilot project	(Dow Jones Institutional News 2013b)
Coyote, New Mexico	United States	Planned, under construction, or undergoing a pilot project	(Valenti 1995)
Freeport, Texas	United States	Constructed	(TCA Regional News, 2020; Bendix 2019)
Logan County, Ohio	United States	Constructed	(Dow Jones Institutional News 2013a)

City	Country	Status of plastic road	Source
Los Angeles, California	United States	Planned, under construction, or undergoing a pilot project	(Waste360 2019)
Maine	United States	Planned, under construction, or undergoing a pilot project	(Steuteville 1996)
North Yarmouth, Maine	United States	Constructed	(Steuteville 1996)
Not specified	United States	Constructed	(Bendix 2019)
Not specified	United States	Constructed	(Noticias Financieras 2020)
Not specified	United States	Planned, under construction, or undergoing a pilot project	(Shoenberger 2000)
Oroville, California	United States	Constructed	(Kuhar 2020)
Richmond, Maine	United States	Constructed	(Steuteville 1996)
Texas	United States	Planned, under construction, or undergoing a pilot project	(Real Estate Monitor Worldwide 2019b)
York, Marine	United States	Planned, under construction, or undergoing a pilot project	(Business Wire 2011)
Not specified	Unknown, Africa	Constructed	(Noticias Financieras 2020)
Anzoategui	Venezuela	Planned, under construction, or undergoing a pilot project	(BBC Monitoring Americas 2016)
Hai Phong	Vietnam	Planned, under construction, or undergoing a pilot project	(Real Estate Monitor Worldwide 2019c)
DEEP C Hai Phong II Industrial Park, Hai Phong	Vietnam	Constructed	(Asia News Monitor 2021)

By reviewing news articles and businesses in the S&P Capital IQ database, we identified multiple companies that either focus on the use of plastic waste as their primary business (as reported by the company) or for larger companies, as one part of their larger business. These companies can be found in Table 14. We also identified the geographic location of the company headquarters for those companies whose primary focus is the use of plastic waste in road construction. For those companies that have a large portfolio in which the use of plastic waste in road construction is one of a suite of products, we identified the geographic location of at least one arm of the company that focused on the use of plastic waste in road construction.

Table 14.
Businesses using plastic waste in road construction identified in S&P Capital IQ database

Company name	Geographic location of business
Advanced Asphalt Technology	United States
Alex Fraser Group	Australia
AXION International Holdings, Inc.	United States
DEEP C Industrial Zones	Vietnam
Dow	Singapore
Dow Mexico	Mexico
Dow Vietnam Company	Vietnam
Downer	Australia
GreenMantra Technologies	Canada
Intergen Energy	Scotland
Inversiones Plasticas Tpm Industrial SL	Mexico
JRD Infratech	India
KK Plastic Waste Management	India
KWS	Netherlands
MacRebur	Scotland
NELPLAST Ghana Limited	Ghana
Rourkela Steel Plant	India
San Miguel Corp. (SMC)	Philippines
TechniSoil Industrial	United States
TrueGrids	United States
Ventia	Australia
Vinci Construction	France
VolkerWessels	Netherlands
Wavin	Netherlands

Annex F.

Life cycle analysis of the use of plastic waste in road construction

We identified four studies in Web of Science that evaluated the use of recycled plastic from an LCA perspective: Lastra-Gonzalez et al. 2021; Santos et al. 2018, 2021; Vila-Cortavitarte et al. 2018. The following data points were collected and can be found for each study: country, primary data (yes/no), LCA database, functional/declared unit, plastic type, wet/dry process, % bitumen replaced, impact assessment, and impact categories. These studies are difficult to compare and contrast, given the differences in assumptions, scope, and inputs and outputs between studies. Examples of the categories in which the authors made assumptions are as follows:

- Lastra-Gonzalez et al. (2021): energy consumed, atmospheric emissions, waste separation process, distance travelled, diesel needed to construct the road, life expectancy of mixture, recyclability of mixtures, and material/process costs
- Santos et al. (2018): durability of the pavement and asphalt plant energy
- Santos, et al. (2021): collection, sorting, and shredding
- Vila-Cortavitarte et al. (2020): maintenance, lifetime expectancy, reclaimed asphalt pavement (RAP), recyclability, and feedstock energy.

This is just one example of how comparison between LCA studies can be difficult. We provide a summary of the overall results of these studies to share findings across different studies, not with the goal of comparing/contrasting studies in mind, but rather to provide a high-level overview of what is known.

A summary of the country, primary data (yes/no), LCA database, functional/declared unit, plastic type, wet/dry process, % bitumen replaced, impact assessment, and impact categories in the LCA studies reviewed (Lastra-Gonzalez et al. 2021; Santos et al. 2018, 2021; Vila-Cortavitarte et al. 2018) can be found in Table 15.

Table 15.
Summary of LCA studies reviewed

Citation	Lastra-Gonzalez et al. 2021
Country	Spain
Primary data (Yes/No)	Yes
LCA Database	Eldan Recycling AS machinery catalogue, de Fomento, 2016, CYPE Ingenieros, 2019
Functional/declared units	**Functional Unit**: 1 km lane with a width of 3.5 m with wearing, binder, and base layers that are 4, 10, and 10 cm thick.
Plastic type	Cable plastic and the film fraction from household packaging
Wet/Dry Process	Wet, dry
% bitumen replaced	**Wet**: 25% **Dry**: 25%
Impact assessment	ReCiPe 2016
Impact categories	Economic, human health, ecosystem diversity, and resource availability

Citation	Santos et al. 2021
Country	Australia
Primary data (Yes/No)	Yes
LCA Database	AusLCI database
Functional/declared units	**Declared Unit 1**: provision of 1 ton of recycled plastic pallets **Declared Unit 2**: provision of the quantity of polymer-modified bitumen **Declared Unit 3**: provision of the quantity of asphalt mix
Plastic type	LDPE, HDPE
Wet/Dry Process	Wet, dry
% bitumen replaced	**Wet**: 0%, 2%, 4%, 6% 8%; **Dry**[3]: 0%, 2.5%, 5%, 10% 20%
Impact assessment	Centrum voor Millikunde Leiden (CML) baseline using Best Practice Guide for Mid-Point Life Cycle Impact Assessment in Australia
Impact categories	Climate change, acidification, eutrophication, ozone layer depletion, and photochemical oxidation

3 Quarry aggregate replacement.

Citation	Santos et al. 2018
Country	France
Primary data (Yes/No)	Yes
LCA Database	EcoInvent Database version 3.2
Functional/declared units	**Functional Unit**: A typical French highway section of 1 km length, composed of two independent roadways, each with 2 lanes with an individual width of 3.5 m.
Plastic type	Waste nitrile rubber from shoe sole and EVA
Wet/Dry Process	Unspecified
% bitumen replaced	2%, 5%
Impact assessment	International Reference Life Cycle Data System (ILCD) impact assessment method at midpoint level
Impact categories	Climate change, freshwater and terrestrial acidification, freshwater ecotoxicity, freshwater eutrophication, ecosystem quality-ionizing radiation, marine eutrophication, terrestrial eutrophication, carcinogenic effects, human health-ionizing radiation, non-carcinogenic effects, ozone layer depletion, photochemical ozone creation, respiratory effects, land use, mineral, fossils, and renewables

Citation	Vila-Cortavitarte et al. (2020)
Country	Spain
Primary data (Yes/No)	No
LCA Database	GaBi
Functional/declared units	**Functional Unit**: 1 km of road
Plastic type	Polystyrenes: Crystal Polystyrene, High Impact Polystyrene, and Polystyrene from hangers
Wet/Dry Process	Dry
% bitumen replaced	1%, 2%
Impact assessment	ReCipe 1.08
Impact categories	Agricultural land occupation, climate change ecosystems, climate changes humans, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionizing radiation, marine ecotoxicity, metal depletion, natural land transformation, ozone depletion, particulate matter (PM) formation, photochemical oxidation, terrestrial acidification, terrestrial ecotoxicity, and urban land occupation

Note: Studies that used both primary and secondary data from an LCA database were considered to have used primary data. In this case, the LCA database used was also reported.

Lastra-Gonzalez et al. (2021) found that, overall, the use of plastic waste from copper cables and film from household packaging to replace 25 percent of bitumen in road construction can achieve up to 11 percent reductions compared to conventional road construction. The plastic from copper cables was found to be more environmentally friendly than the film and was found to have environmental impact reductions between 17.2 and 20.9 percent. The sustainability of the roads was tied to the service life of the road and was also found to be less impactful if the whole pavement was evaluated compared to the binder only.

Santos et al. (2021) found that the use of LDPE and HDPE waste can lead to environmental reductions generally in all indicators in comparison to virgin polymer and virgin quarry aggregates. For instance, replacing 8 percent of virgin Polyethylene and styrene-butadiene-styrene (SBS) with recycled soft plastic waste using the wet method led to about a 10 percent and 16 percent decrease, respectively, in carbon dioxide (CO_2) equivalent emissions. The use of rigid recycled plastic as a substitute for quarry aggregate using the dry method had less environmentally friendly results, showing an increase of about 20 percent in CO_2-equivalent emissions.

Santos et al. (2018) studied the use of waste nitrile rubber from shoe sole and EVA in bitumen modification and found that if the waste modifier improved the performance of the road, environmental benefits will be seen no matter the type of polymer or percentage used. The greatest environmental benefits were realized when 5 percent waste nitrile rubber modified bitumen, which had the highest environmental reductions in ozone layer depletion (21 percent) and lowest environmental reductions in freshwater eutrophication (9 percent).

Vila-Cortavitarte et al.(2018) conducted an LCA of the use of PS waste in road construction and found that environmental benefits are expected to occur only when considering enhanced road behavior. The life expectancy of the road is expected to increase when PS from hangers is used in road construction (as determined by engineering performance tests conducted in the laboratory as a part of this study). Environmental reductions increased as the life extension of the road increased.

Annex G.

Asphalt mixtures tested in leaching studies

The specific mixtures evaluated in both studies (Fernandes, Silva, and Oliveira 2019a, b) include the following:

- Stone mastic asphalt (SMA) reference material
- SMA with commercial modified bitumen (no waste)
- SMA with modified bitumen with 10 percent waste motor oil and 6 percent HDPE
- SMA with modified bitumen with 10 percent waste motor oil and 5 percent SBS
- SMA with modified bitumen with 7.5 percent waste motor oil and 20.0 percent crumb rubber (Fernandes, Silva, and Oliveira 2019a).

Fernandes, Silva, and Oliveira (2019b) study also evaluated the following additional SMA mixtures:

- SMA with bitumen modified with 15 percent recycled engine oil bottoms and 6 percent HDPE)
- SMA with bitumen modified with 15 percent recycled engine oil bottoms and 5 percent SBS)
- SMA with bitumen modified with 15 percent recycled engine oil bottoms and 20 percent crumb rubber.

Seven recycled SMA mixtures with 50 percent of reclaimed asphalt pavement (RAP) and plastic waste were also tested in this study (Fernandes, Silva, and Oliveira 2019b). All the following samples include recycled SMA while each varies in bitumen modification:

- Conventional bitumen B160/220 and 0.3 percent fibers
- Bitumen modified with 15 percent engine oil and 6 percent HDPE
- Bitumen modified with 15 percent engine oil and 5 percent SBS
- Bitumen modified with 15 percent engine oil and 20 percent crumb rubber
- Bitumen modified with 17.5 percent recycled engine oil bottoms and 6.0 percent HDPE
- Bitumen modified with 17.5 percent recycled engine oil bottoms and 5.0 percent SBS
- Bitumen modified with 22.5 percent recycled engine oil bottoms and 20.0 crumb rubber (Fernandes, Silva, and Oliveira 2019b).

Fernandes, Silva, and Oliveira (2019a) evaluated waste HDPE (4 percent, 5 percent, and 6 percent by weight of bitumen), SBS (4 percent, 5 percent, and 6 percent by weight of bitumen) and crumb rubber (5 percent, 7.5 percent, 10 percent, 15 percent, and 20 percent by weight of bitumen) as binder modifiers in SMA mixtures. The modified SMA mixture (binder content 5.8 percent) then underwent mechanical testing, surface characterization, and environmental characteristics to teach leaching according to EN 12457 (Fernandes, Silva, and Oliveira 2019a). This standard uses spectroscopic methods to evaluate heavy metal presence in eluate (Fernandes, Silva, and Oliveira 2019a). In this test, the sample is dried, placed in a closed container with distilled water, and agitated for 24 hours (Fernandes, Silva, and Oliveira 2019a). Then, the suspended solids are allowed to settle and solids are filtered from liquids. The liquid portion (eluate) is then analyzed to quantitatively measure leached heavy metals (Fernandes, Silva, and Oliveira 2019a).

The heavy metals measured in both studies are Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Lead (Pb), and Zinc (Zn) (Fernandes, Silva, and Oliveira 2019a). The results of Fernandes, Silva, and Oliveira (2019a) primarily indicate that leaching of certain heavy metals is not beyond legal limits outlined in the Portuguese Decree-Law no. 183/2009. For Cd, Cr, Ni, and Pb, the samples containing HDPE and SBS had less than or equal to the same amount of each metal as the reference material (Fernandes, Silva, and Oliveira 2019a). However, for Cu, the bitumen modified with new modified binder had higher levels of Cu than the reference material; this sample still fell below the limits, so it is not a concern (Fernandes, Silva, and Oliveira 2019a). All values fell below the limits set by the Portuguese law for Zn; however, all mixture samples containing SBS, HDPE, or crumb rubber had slightly higher levels of Zn than the new modified binder (Fernandes, Silva, and Oliveira 2019a). The sample containing SBS also had higher levels of Zn than the reference material (Fernandes, Silva, and Oliveira 2019a). Zn may be a potential concern, but since all values fall well within the reference limit, this is unlikely to be a major issue for plastic roads, in comparison to conventional roads.

In Fernandes, Silva, and Oliveira (2019b) two samples incorporating waste material had higher levels than control values:

1. SMA with bitumen modified with 15 percent recycled engine oil bottoms and 6 percent HDPE, and
2. SMA with bitumen modified with 10 percent waste engine oil and 5 percent SBS.

The SMA mixture with 6 percent HDPE had higher levels of Cu (0.31 mg per kg) than both control mixtures, which lacked recycled engine oil bottoms and HDPE (< 0.25 mg per kg) (Fernandes, Silva, and Oliveira 2019b). The legal limit for Cu is 2 mg per kg, so the values still fall well within legal limits. The mixture with 10 percent engine oil and 5 percent SBS had 0.49 mg per kg of Zn, which was greater than one of the controls, control SMA with conventional bitumen B35/50 and 0.3 percent fibers, which had 0.43 mg per kg (Fernandes, Silva, and Oliveira 2019b). Interestingly, the samples that incorporated RAP had higher levels of Ni and Zn (though still within the limits set by Portuguese law), potentially due to the accumulation of fuel and engine oil on the pavement and tire and brake pad abrasion (Fernandes, Silva, and Oliveira 2019b). RAP is widely used, so this may be a future concern as RAP continues to be recycled in the future.

Annex H.

Microplastic generation

Modeling by Evangeliou et al. (2020) estimated that the annual tire and brake wear microplastic emissions in Asia is the following:

- 4.8–30 kilotons of PM2.5-size tire wear particles
- 85.0–167 kilotons of PM10-size tire wear particles
- 26–62 kilotons of PM2.5-size brake wear particles
- 50–67 kilotons of PM10-size brake wear particles.

These estimates were obtained using top-down estimates of total tire wear emissions based on data reported for Norway, Sweden, and Germany (Evangeliou et al. 2020). On the other hand, Brahney et al. (2021) measured the deposition of microplastics in the western United States through the National Atmospheric Deposition Network and then modeled it outward. To our knowledge, none of the areas where primary data were collected prominently use recycled plastic waste on roads (compared to India, for example), so we can assume that these data likely represent the road traffic microplastic emissions primarily from conventional roads.

Annex I.

Laboratory binder characterization

Recycled plastic waste can be incorporated into binder and graded according to penetration-, viscosity-, and/or Superpave Performance Grading-based measures to determine binder suitability. Superpave Performance Grading is considered the most modern specification system and viscosity tests are preferred over penetration tests (Islam and Tarefder 2020). In the Superpave Performance Grading specification system, each test is assigned a certain temperature at which it should be conducted so researchers can determine the climate and traffic conditions at which the binder can reliably perform in the field. Frequently applied tests are provided in Table 16. These laboratory binder characterization tests allow researchers to assign binders a 'grade', which corresponds to the results of the test. For example, a viscosity grade of AC-2.5 corresponds to virgin asphalt cement (AC) with a viscosity of approximately 250 poises at 60^{o}C. The asphalt binder grading nomenclature shares the range of temperatures at which a binder can perform properly. In addition to the tests shown in Table 16, laboratory binding characterization can also evaluate the use of recycled plastic in the binder evaluated by using softening point and ductility tests (Willis, Yin, and Moraes 2020).

Table 16.

Examples of standardized tests by the American Society for Testing and Materials (ASTM) and American Association of Highway and Transportation Officials (AASHTO) associated with laboratory binder characterization.

Characterization category	Example studies using these test(s)	Test(s)
Penetration	Ahmedzade et al. 2017; Al Helo Qasim, and Abdulhussein 2020; Bary et al. 2019; Guru et al. 2014; Leng, Padhan, and Sreeram 2018; Leng et al. 2018; Padhan et al. 2020; Padhan and Sreeram 2018; Sojobi, Nwobodo, and Aladegboye 2016; Ye et al. 2021	ASTM D946
Viscosity	Ahmedzade et al. 2017; Cai et al. 2019; Khan et al. 2016; Padhan et al. 2020; Ye et al. 2021	ASTM D 3381, AASHTO M 226
Performance Grading	Ahmedzade et al. 2017; Al Helo, Qasim, and Abdulhussein 2020; Balaguera et al. 2018; Bary et al. 2019; Guru et al. 2014; Kabir et al. 2021; Khan et al. 2016; Leng, Padhan, and Sreeram 2018; Zhang et al. 2020	Superpave Performance Grading, AASHTO M 320, and AASHTO M 332

Source: Islam and Tarefder 2020.

Synthesis of scientific literature

Studies evaluating plastic roads using these tests consistently found that recycled plastic binders reduced penetration and ductility and increased the softening point, viscosity, and high-temperature performance grade (Willis, Yin, and Moraes 2020). It is expected that recycled plastic binders will improve the rutting resistance of roads, compared to conventional road construction (Willis, Yin, and Moraes 2020). However, often factors that improve rutting resistance decrease cracking. Few studies were noted (Willis, Yin, and Moraes 2020) as evaluating low-temperature cracking and fatigue.

When using the wet process, phase separation between the asphalt binder and recycled plastic was noted as an issue in the use of this pavement over the long term (Vasudevan et al. 2012; Willis, Yin, and Moraes 2020). Due to the solubility and thermodynamics of the two materials used to create a plastic road (that is, binder and recycled plastic), the materials can separate from one another under static heated storage conditions, which can be troublesome for road performance (Willis, Yin, and Moraes 2020). ASTM D7173 is used in part to evaluate the storage stability of binders (Willis, Yin, and Moraes 2020). Additionally, a test called the laboratory asphalt stability test was developed to test phase separation, which was not fully addressed in the previous Superpave Performance Grading (Bahia et al. 2001). Researchers consistently found that phase separation was an issue for recycled plastic and binders; as such, multiple researchers incorporated a stabilizer[4] into the binder and recycled plastic blend (Willis, Yin, and Moraes 2020).

4 Examples of potentially effective stabilizers include EVA, maleic anhydride (MA) grafted LLDPE, nanosilica, organic montmorillonite, polyphosphoric acid (PPA), reactive elastomeric terpolymer (RET), and SBS as well as low-level chlorination and maleation of *Polyethylene* (Willis, Yin, and Moraes 2020).

Annex J.

Laboratory mixture characterization

Historically, rutting[5] and cracking are the two major concerns that engineers focused on to determine if a new asphalt mixture was fit to build a road. The use of plastic waste is thought to improve rutting resistance but may decrease cracking resistance in comparison to conventional roads. From the late 1980s to early 1990s, the U.S. Strategic Highway Research Program created the Superpave mix design technique, which aimed to create asphalt mixes that greatly improved the rutting performance of roads in early stages, though now asphalt cracking performance is the primary concern (Islam and Tarefder 2020). However, rutting and cracking performance is not a part of the standard Superpave mixture design. Rather, Superpave only uses the tensile strength ratio test to determine if the asphalt mixture has adequate moisture damage resistance. Therefore, relying only on the Superpave mixture design does not ensure that plastic roads have adequate performance. Superpave specifications that apply to asphalt binders are newer than the Marshall Stability Tests, applied to asphalt mixtures. Overall, though, in more recent years, concern when creating new asphalt binder mixes has been focused on the cracking of roads, instead of rutting (Islam and Tarefder 2020). Example tests for mixture properties can be found in Table 17.

5 Defined as the "the load-induced permanent deformation of a flexible pavement" (White et al. 2002).

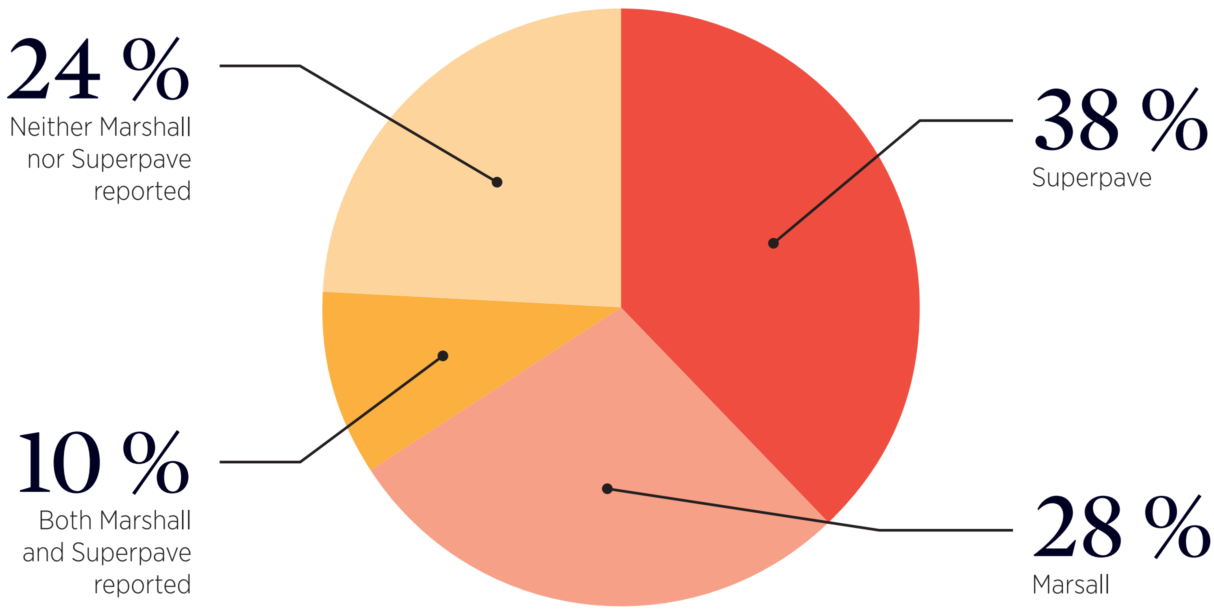
Table 17.
Common laboratory tests and tests standards to assess asphalt mixture properties.

Mixture property	Example studies using these test(s)	Laboratory test(s)	Example of test standard
Cracking	(Fernandes, Silva, and Oliveira 2019a; Mazouz and Merbouh 2019; Vila-Cortavitarte et al. 2018)	Disk-Shaped Compact Tension Test	ASTM D7313-13
		Indirect Tensile (IDT) Test	AASHTO T 322-07
		Semi-Circular Bend (SCB) Test	AASHTO TP 105-13
		Thermal Stress Restrained Specimen Test	BS EN12697-4
		Disk-Shaped Compact Tension Test	ASTM D7313-13
		Texas Overlay Test	TxDOT Tex-248-F
			NJDOT B-10
		Illinois Flexibility Index Test	AASHTO TP 124-16
		Direct Tension Cyclic Fatigue Test	AASHTO TP 107-14, AASHTO TP 133-19

Mixture property	Example studies using these test(s)	Laboratory test(s)	Example of test standard
Cracking	(Fernandes, Silva, and Oliveira 2019a; Mazouz and Merbouh 2019; Vila-Cortavitarte et al. 2018)	Flexural Bending Beam Fatigue Test	AASHTO T 321
			ASTM D7460
		IDT Fracture Energy Test	N/A
		Illinois Flexibility Index Test	AASHTO TP 124-16
		SCB at Intermediate Temperature	LaDOTD TR 330-14
			ASTM D8044-16
		Texas Overlay Test	TxDOT Tex-248-F
		Direct Tension Test	n.a
		IDT Energy Ratio Test	n.a
		Illinois Flexibility Index Test	AASHTO TP 124-16, IDEAL CT ASTM D8225-19
Rutting	(Khurshid et al. 2013)	Asphalt Pavement Analyzer	AASHTO T 340
		Flow Number	AASHTO TP 79-15
		Hamburg Wheel Tracking Test	AASHTO T 324
		Superpave Shear Tester	AASHTO T 320-07
		Triaxial Stress Sweep Test	AASHTO TP 116-15
Moisture susceptibility	(Al Helo, Qasim, and Abdulhussein 2020; Khurshid et al. 2013)	Hamburg Wheel Tracking Test	AASHTO T 324
		Tensile Strength Ratio	AASHTO T 283

Source: West et al. 2018.

Figure 8.
Use of Marshall Stability Test and/or Superpave Performance Grading



The civil engineering discipline related to road construction has developed several laboratory tests, some of which have associated standards that are used to test if asphalt mixtures perform suitably. These tests and standards are widely accepted and choice between which test to conduct varies across stakeholders and geographies. Consensus is still building about which tests is the 'best' test to conduct.[6]

Synthesis of scientific literature

Despite the more recent use of Superpave Performance Grading instead of the Marshall Stability Test, Willis, Yin, and Moraes (2020) found that many studies conducting laboratory mixture characterization of plastic roads used the Marshall Stability Test and/or Marshall specifications, as reported by the authors. We did not attempt to review studies to determine if they met Marshall and/or Superpave specifications, but rather relied on the reported designations by the authors. Of the 29 studies evaluating the engineering performance of plastic roads, our study found that most studies, 25 scientific articles in this case, used either the Marshall Stability, Superpave Performance Grading, or both tests/specifications. We found that the Superpave Performance Grading and related specifications were used more commonly than its predecessor, the Marshall Stability Test (Figure 8). In most cases, the addition of recycled plastic to the asphalt mixture increased Marshall stability, which, many indicated, would improve road resistance to permanent deformation (Willis, Yin, and Moraes 2020).

6 Within the United States, for example, states vary in their use of preferred rutting tests (West et al. 2018). In North Carolina, Oregon, and Arkansas, for instance, the Asphalt Pavement Analyzer (AASHTO T 340 is the current rutting test used whereas in Texas, Maine, Utah, and California, among other states, the Hamburg Wheel Tracking Test (AASHTO T 324) is currently used (West et al. 2018). Overall, most states use the Hamburg Wheel Tracking Test to test rutting followed by the AASHTO T 340. However, the less popular rutting tests, such as the Flow Number, which is currently used in Delaware, is still accepted, just not as widely used.

Annex K.

Cost-Effectiveness Analysis (CEA) of Plastic Roads

Plastic roads bring an interesting circular economy and development-related option. The problems related to the utilization of plastic waste persist across the globe, but they are particularly acute in East Asia and the Pacific and South Asia Region. The notion of using plastic in road construction is not new, as this technology was patented in 1974. Since then, the solution has been available to the masses free of charge. Its simplicity and direct applicability facilitated plastic roads' construction in several countries worldwide: India, Sri Lanka, United Kingdom, Canada, or the United States, to name a few.[7]

The concept of plastic roads seems promising, but is the economics convincing enough? It is expected that plastic utilization in road construction can help manage plastic waste and prevent its negative impact on the environment. Combining the circular economy narrative with the alleged longer life-span for plastic roads and more extended durability for maintenance with similar or better road performance tests and allegedly cheaper inputs with recycled plastic replacing a proportion of bitumen constitute a simple recipe for a potentially successful and scalable development solution. If verified financially and economically and implemented through a technologically standardized and transparent process, this solution could efficiently deliver a worthwhile investment option for developing countries, where the scarcity of paved and properly managed roads is frequently intertwined with the mounting problem of plastic waste management.

The financial aspects of road construction are crucial from the industry point of view. For the industry, any new solution needs to be cost-effective to be viable and scalable. But recently, the financial aspects of road construction are becoming more intertwined with the economic aspects as road paving is energy demanding and uses scarce natural resources.[8] Traditional road building can negatively influence the environment and bring economic costs that generally should be accounted for from the point of view of the entire society. At the same time, a rise in the use of natural resources due to the necessity for the construction of more roads to connect more people with markets and the presence of competing uses for scarce natural resources can increase financial expenditures.[9] Therefore, the presence of a financially viable offsetting mechanism could potentially be of interest to the road construction industry in developing countries.

Plastic roads are usually constructed though two types of plastic utilization processes.[10] The inclusion of recycled plastic in road construction can generally be done through a wet or dry process where plastic is primarily used as a bitumen modifier (<10 percent bitumen replacement). The dry and wet methods differ slightly, with the dry process being generally considered a preferred option, especially in the context of developing countries where optimal monitoring of processes can be hard. Furthermore, the Indian Road Congress has already set the dry process standards that might constitute a practical reference point for other countries in the region. Consequently, the dry process

7 The original patent has been adjusted for the specific needs of different countries and various companies that specialize in this technology. Also, to various extents, both dry and wet processes have been employed.

8 The volume of fuel used to transport aggregates and other materials necessary for road construction and the energy used to power road machinery and equipment is significant. These factors add to the economic costs of road construction through emissions and natural resource depletion.

9 Because the growth in demand for natural resources due to a growing demand for roads and competing uses for scarce resources can increase the prices of these inputs adding to the financial costs of road construction.

10 These processes are described in more detail in the text of this report, specifically in Table 2 and the following text.

of plastic utilization in road construction is being considered in the following analysis.

The rigorous economic analyses of plastic roads are virtually non-existent. The results of a few quantitative studies that are available in peer-reviewed publications frequently contain outdated data, show a scarcity of financial and economic variables, present unclear and hard to trace data sources or unconvincing methodological approaches. Furthermore, the results of these economic analyses can even be contradictory.[11]

Methodology

The CEA is pursued to verify the economics of plastic roads. The economic analysis pursued in this report has modest aspirations that are bound by a general lack of the necessary data, especially on the benefits side. The persistent lack of information about potential changes in benefits between standard bitumen roads and plastic roads prohibits the use of a classic cost-benefit analysis (CBA), which would typically constitute the preferred methodological approach in this case. To set up a CBA properly, we would need to compare 'business-as-usual scenario' and 'intervention scenario' in the case of a specific road in a particular location. This would allow the quantification of potential changes in benefits: change in traffic volume and type, change in travel times and the onset of accidents, change in fuel usage or maintenance of vehicles, and similar parameters. In this report, as a second-best option, a CEA, is employed instead. The CEA is pursued using more general assumptions by considering the construction of a plastic road and applying a dry plastic utilization process in India's context.[12] The standard CEA allows the estimation of economic benefits in the number of units produced when intervention is put in place instead of including direct valuation of these benefits. The goal of the CEA is to find out if investing in plastic roads could potentially produce higher benefits to the whole society and higher gain per unit of expenditure than the construction of standard bitumen roads. The effectiveness ratio of the road construction costs-to-benefits is measured using the utility of 1 km of constructed road. The following cost-effectiveness ratio is being used:

$$CE_i = \frac{PV\ of\ Costs_i}{PV\ of\ Effectiveness_i}$$

Where:

CE_i = Cost effectiveness ratio

PV of $Costs_i$ = Present Value of all costs measured at economic resource level.

PV of $Effectiveness_i$ = Effectiveness measured per 1 km of constructed road.

Modeling Assumptions

A set of the essential modeling assumptions used in the modeling process is presented in Table 18. These assumptions were necessary to set up an 'existing scenario' (business-as-usual scenario') and 'intervention scenario' that could be directly compared in the CEA to deliver initial conclusions regarding the cost-effectiveness of both road types.

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11 While most reports that include some economic analysis state that plastic roads are more economical (for example, Vasudevan et al. 2012), others claim that they are, in fact, more expensive than standard roads (for example, KPMG 2021 report). There might be several issues associated with these differences in economic results, and these elements can have individual or combined effects: (1) various reports might have different assumptions, (2) the reports might also assess different road types in different locations, (3) the reports might analyze plastic waste use as bitumen replacement versus bitumen modifier, (4) various types of bitumen might be considered (prices differ depending on class of bitumen and its origin) (the same might apply to costs of the aggregate), and (5) the reports might include and mix different categories of costs (for example, some financial expenditures and revenues might be combined with economic costs and benefits) and so on.

12 India was chosen in this modeling exercise because it remains a pioneer in plastic roads. Also, the information regarding the construction of plastic roads in India was the most available.

Table 18.

Modeling assumptions

	Existing scenario: standard bitumen road construction	Intervention scenario: plastic road construction (dry process)
1.	(a).The construction of a new/penetration road is assumed. (b). No recycling of asphalt pavement is assumed. The road is constructed from new aggregate materials and bitumen. (c). The analysis assumes 1 km of road that is 3.75 m wide with thickness of 25 mm semi-dense bituminous concrete (SDBC) -3,750 m^2. (d).Flexible pavement road is assumed.	(a).The construction of a new/penetration road is assumed. (b). No recycling of asphalt pavement is assumed. The road is constructed from new aggregate materials and bitumen+ a proportion of recycled plastic. (c).The analysis assumes 1 km of road that is 3.75 m wide with thickness of 25 mm SDBC – 3,750 m^2. (d). Flexible pavement road is assumed.
2.	(a) The road is constructed from bitumen and aggregate. The same type of bitumen and aggregate is assumed, as is the case of the plastic road. (b) The contractor in charge of laying the road gets ready bitumen mix from the plant.	(a) Standardized quality and size ready to use in the dry process plastic is purchased and delivered to the asphalt plant by the recycling company. The price of recycled plastic includes all costs associated with plastic recycling, cleaning, and transport to the asphalt plant. (b) No additional costs are involved on the asphalt plant's side (no new equipment is needed and the same temperature is required for the bitumen-plastic mix as for the standard bitumen mix). Plastic is mixed with heated aggregate (at 140–175^{0}C) and then combined with the already heated bitumen. The traditional bitumen road process differs from the dry process only when plastic is added to the heated aggregate. (c. The contractor in charge of laying the road gets ready bitumen-plastic mix from the plant.[13]
3.	(a) It is assumed that aggregate and bitumen costs are the same in the case of both road types. (b) Both road types require the same equipment type for laying the asphalt. The surface preparation before laying the asphalt is also assumed to be the same in the case of both road types.	
4.	(a) 80/100 bitumen is assumed. For 1 km road as specified in Table 2 point (1) it is assumed that 11.25 tons of bitumen are required.	(a) It is assumed that 10% of bitumen in the standard road composite is modified with plastic. Therefore, 1.125 tons of plastic are used instead of bitumen. The costing of bitumen is based on this distribution. Consequently, plastic road requires 10.125 tons of bitumen. (b) The plastic type assumed in dry process is LDPE.[14]
5.	(a) The life of a traditional bitumen road is assumed at 20 years. End of life of a road is understood as the time when the road is abandoned and there will be a decision made if it will be reconstructed or left as it is. (b) Maintenance is assumed to be pursued every 5 years. Therefore, there are 3 maintenance activities assumed within 20 years. (c) It is assumed that the overlay work is pursued in Year 10 after construction.	(a) The life of a bitumen-plastic road is assumed at 20 years. The end of life of a road is understood as the time when the road is abandoned, and a decision will be made if the road should be reconstructed or left as is. (b) Maintenance is assumed to be pursued every 7 years. Therefore, there are 2 maintenance activities assumed within 20 years. Lower deterioration rate of plastic roads is assumed, based on the past research on roads in Pune (Biswas, Goel, and Potnis 2020). (c) It is assumed that the overlay work is pursued in Year 10 after construction.
6.	(a) Assumed financial price per 1 ton of domestic bitumen (VG 10 (80/1000)[15] = Indian rupee (INR) 36,830 per ton ex-Mumbai (bulk bitumen).[16]	

13 Source: https://e360.yale.edu/features/how-paving-with-plastic-could-make-a-dent-in-the-global-waste-problem.

14 Source: https://law.resource.org/pub/in/bis/irc/irc.gov.in.sp.098.2013.pdf.

15 This type of bitumen was used in analysis reported in Vasudevan et al. 2012.

16 Price obtained on August 16, 2021, from https://www.bitumenindia.com/.

	Existing scenario: standard bitumen road construction	Intervention scenario: plastic road construction (dry process)
7.	n.a.	(a) Assumed financial price of recycled plastic for dry process per 1 ton: INR 20,000 per ton[17] (per 1.125 tons = INR 22,500)
8.	n.a.	(a) Assumed reduction in carbon dioxide (CO_2) emissions: 3.5 tons of CO_2 per 1 km of road (Source: Vasudevan et al. 2012).
9.	n.a.	(a) Pricing of CO_2 according to the World Bank's 'Guidance Note on Shadow Pricing of Carbon in Economic Analysis', dated November 12, 2017.[18]
10.	n.a.	(a) The potential economic costs of leaching of plastic and possible creation of various by-products (for example, gases and micro and nano plastics) are ignored due to the lack of quantitative information on this topic. (b) The assumed dry process is expected to create no toxic gases due to max temperature of 180 Celsius.[19]
11.	(a) Economic costs associated with road usage: traffic volume and type, the opportunity cost of travelling time, maintenance requirement for cars using the road, accidents' rate and associated mortality rate, and so on are also ignored due to the lack of the specific location of the road and associated data (Note: unspecified road location in India is assumed in the case of both road types). (b) In the evaluation of carbon release associated with both road types, only emissions associated with the road construction, maintenance, and overlay were quantified. All other emissions are ignored due to the lack of specifics as a generic type and location of Indian road is assumed.[20]	
12.	(a) VAT on goods is assumed to be at 18%. (b) The economic discount rate was assumed at 12%. (c) Tariffs on bitumen, aggregates, and plastic are assumed at 10%. (d) Transportation and handling costs were assumed at 5%. (e) Foreign exchange premium was assumed at 1% (based on 2018 trade data). (f) No subsidies were included in calculation of conversion factors due to the lack of information on this topic.	
13.	The CEA outcome is measured in kilometers of road built. In this case it is 1 km of constructed road that brings utility. One outcome is assumed in this analysis due to the lack of data on other potential benefits.[21]	
14.	(a) It is assumed that the emission of CO_2 per 1 km is at 48.4 tons (construction phase) and 2.71 tons of CO_2 per 1 km for the maintenance phase (distributed equally into 3 maintenance activities). (b) The volume of carbon emissions at the overlay work in Year 10 after construction is assumed at 50% of the original construction emissions, hence 24.2 tons of CO_2.	(a) It is assumed that 1 km of plastic road reduces 3.5 tons of CO_2 as plastic is not burned but instead, it is used in the bitumen mix.[22] Therefore, it is assumed that the construction of 1 km of plastic road produces 48.4-3.5 = 44.9 tons of CO_2 per1 km of road. (b) It is assumed that volume of carbon at maintenance is at 1.81 tons of CO_2 (2.71 tons divided by 3 maintenance activities on a standard road = 0.903 tons of CO_2. Multiplied by 2 maintenance activities in the case of plastic road = 1.81 tons of CO_2). These 1.81 tons of CO_2 are distributed equally into 2 assumed maintenance activities. (c) The volume of carbon emissions at the overlay work in Year 10 after construction was assumed at 50% of the original construction emissions, hence 22.45 tons of CO_2

17 Source: Interview with Green Worms: http://greenworms.org/. Note: it was stated that this price can be further reduced in the case of steady high-volume orders. Sensitivity analysis was pursued on prices of recycled plastic (Table 20).

18 Source: https://pubdocs.worldbank.org/en/911381516303509498/2017-Shadow-Price-of-Carbon-Guidance-Note-FINAL-CLEARED.pdf.

19 Source: https://law.resource.org/pub/in/bis/irc/irc.gov.in.sp.098.2013.pdf.

20 The detailed approach to the carbon footprint estimations and data requirements can be seen in the link below. For this analysis, the emissions of 1 lane road in West Bengal were used as likely the most adequate to our road-type scenarios. https://www.adb.org/publications/methodology-estimating-carbon-footprint-road-projects-case-study-india.

21 Note: If additional environmental or other co-benefits could be estimated, the CEA would be replaced with cost utility analysis (CUA) as the latter allows building of an index to compare various outcomes of a proposed intervention that might have a joint impact. In this analysis, only one outcome is considered due to the lack of data, hence the CEA methodology.

22 Source: Vasudevan et al. 2012.

Results

The results of the CEA suggest that plastic roads are cost-effective. The CEA valuation was pursued over 20 years to account for an assumed life of a road using a discount rate of 12 percent. The results of the pursued analysis show that the construction of plastic roads is likely cost-effective as the present value (PV) of costs in the case of the 'intervention scenario' (when 1 km of plastic road is constructed) is lower than the PV of costs in the case of the 'existing scenario' (business-as-usual scenario) (when 1 km of traditional bitumen road is built). Therefore, the use of recycled plastic in roads construction seems to have its economic rationale. Table 19 presents more details obtained in the CEA.

Table 19.

CEA Results based on economic prices of 1 km of constructed road considering the lower and upper bound of CO_2* pricing (in INR and US$, respectively) **

	Costs of existing scenario (bitumen road)	Costs of intervention scenario (bitumen-plastic road)	Difference in PV of costs between intervention scenario and existing scenario	
PV in INR (considering lower-bound CO_2 pricing)	INR –17,167,146	INR –16,722,975	INR –444,171	Costs savings in the case of plastic roads
PV in US$ (considering lower-bound CO_2 pricing)	US$ –156,065	US$ –152,027	US$ –4,038	Costs savings in the case of plastic roads
PV in INR (considering upper-bound CO_2 pricing)	INR –17,440,577	INR –16,975,638	INR –464,939	Costs savings in the case of plastic roads
PV in US$ (considering upper-bound CO_2 pricing)	US$ –158,551	US$ –154,324	US$ –4,227	Costs savings in the case of plastic roads

Note: The differences in cost savings between lower and upper carbon valuation depend on CO_2 annual valuation, as prescribed by the World Bank in November 2017 Shadow Pricing of carbon Guidance Note: https://pubdocs.worldbank.org/en/911381516303509498/2017-Shadow-Price-of-Carbon-Guidance-Note-FINAL-CLEARED.pdf.

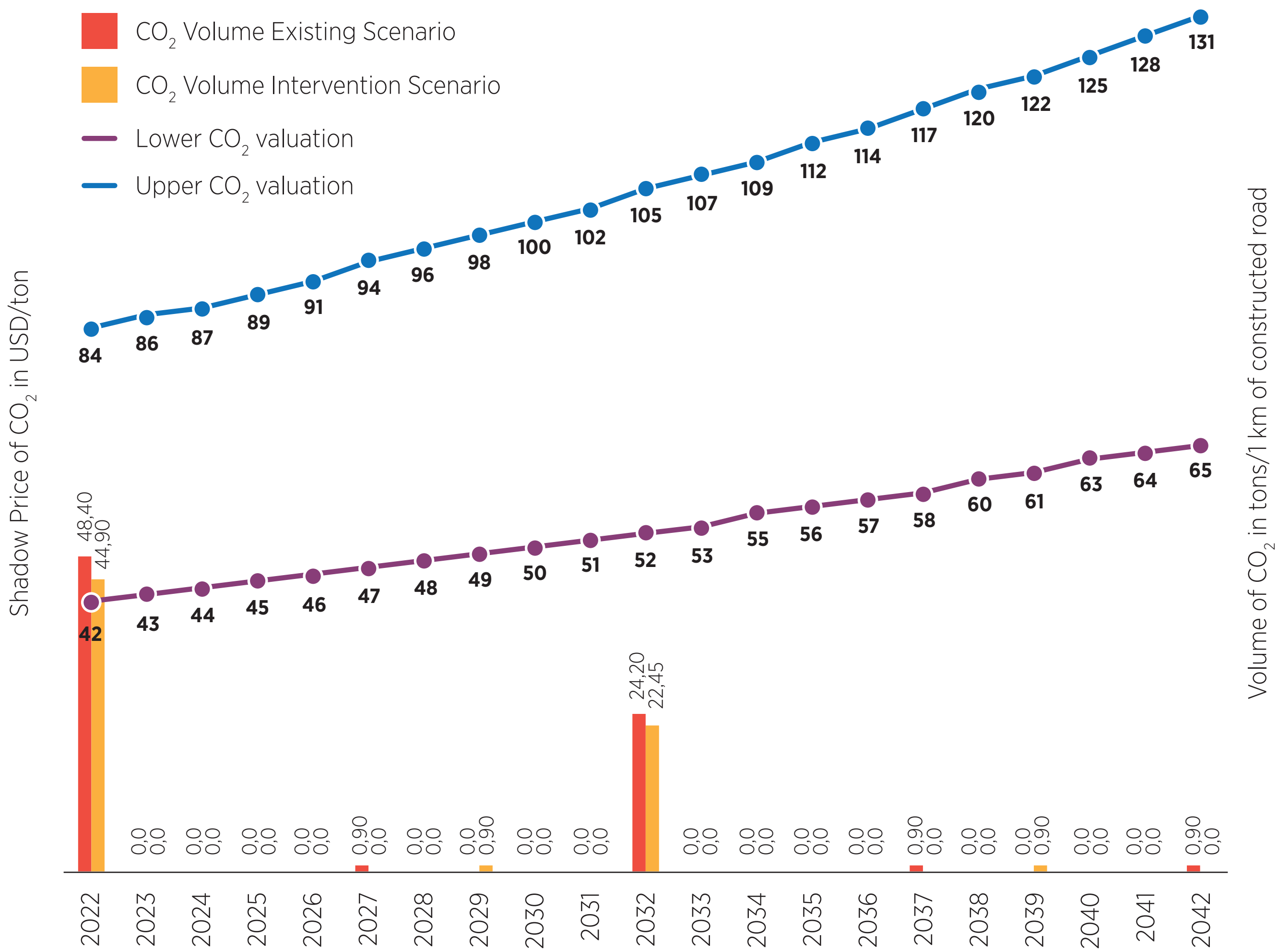
**. The results are based on economic prices (not financial prices) using construction, maintenance, and overlay costs. The costs associated with road usage (traffic, fuel use, or maintenance of cars using each of these two roads) are excluded due to the lack of specifics about the location of the road and traffic data. Consequently, due to the lack of specifics associated with the location of the road, the costs used in this analysis do not include all the expenses related to the typical life cycle cost analysis of a road.

The results obtained in the CEA also support the reality seen on the ground in India, where actual roads that use recycled plastic are being constructed. Therefore, it is expected that plastic roads are not only economically viable, but they can also be financially viable as the industry already engages in the construction of such roads.

The CEA includes the economic pricing of carbon. The CEA includes the valuation of potential carbon co-benefits associated with the use of recycled plastic in roads construction. The CO_2 shadow prices and volumes of CO_2 used in the analysis are presented in Figure 9.

Figure 9.

Shadow prices of CO_2 and volume of CO_2 included in the CEA



Sensitivity analysis shows robust results. A simple sensitivity analysis was pursued on the price of plastic necessary for the construction of the road. The cost of plastic was increased by up to 50 percent. The CEA results show the higher cost-effectiveness of plastic roads and hold when the price of recycled plastic increases from INR 20 per kg to INR 30 per kg. Table 20 shows more numerical details.

The pursued CEA acknowledges some limitations. The presented CEA is general, is not associated with any specific road in India, and holds under the stated assumptions. It is expected that the location of the road and particular arrangements related to the road construction supply chain (for example, transport costs associated with the delivery of aggregate materials, distance from the asphalt plant to road construction, terrain, availability of plastic recyclers that can provide a standardized quality product, the scale of road contractors, and so on.) might influence the costs of road construction. Therefore, it is expected that the cost-effectiveness of plastic roads might be location dependent. It might also be conditioned on road size (scale of the project at hand) and road construction technology (for example, engineering and material/process requirements connected to the specificity of terrain and so on). The data used in this analysis come from various published peer-reviewed resources, with many of them quoting experimental results, industry-specific websites, and interviews with plastic recyclers. It is acknowledged that the available data might have some measurement errors or might be relevant only in the case of a specific road and circumstances stated in the publication. However, no better information was available to pursue this analysis.

Table 20.

Recycled Plastic Price Sensitivity Analysis

Currency: INR						
% Change in recycled plastic price	**PV 'intervention scenario' lower-bound CO_2 pricing**	**PV 'intervention scenario' upper-bound CO_2 pricing**	**PV 'existing scenario' lower-bound CO_2 pricing**	**PV 'existing scenario' upper-bound CO_2 pricing**	**Difference in PV of Costs between 'existing scenario' and 'intervention scenario', lower-bound CO_2 pricing**	**Difference in PV of Costs between 'existing scenario' and 'intervention scenario', upper-bound CO_2 pricing**
[+]50% (INR 30/kg)	–16,731,762	–16,984,425	–17,167,146	–17,440,577	–435,384	–456,152
[+]40% (INR 28/kg)	–16,730,005	–16,982,668	–17,167,146	–17,440,577	–437,141	–457,909
[+]30% (INR 26/kg)	–16,728,247	–16,980,910	–17,167,146	–17,440,577	–438,899	–459,667
[+]20% (INR 24/kg)	–16,726,490	–16,979,153	–17,167,146	–17,440,577	–440,656	–461,424
[+]10% (INR 22/kg)	–16,724,732	–16,977,395	–17,167,146	–17,440,577	–442,414	–463,182
modeled (INR 20/kg)	**–16,722,975**	**–16,975,638**	**–17,167,146**	**–17,440,577**	**–444,171**	**–464,939**

Currency: US$						
% Change in recycled plastic price	**PV 'intervention scenario' lower-bound CO_2 pricing**	**PV 'intervention scenario' upper-bound CO_2 pricing**	**PV 'existing scenario' lower-bound CO_2 pricing**	**PV 'existing scenario' upper-bound CO_2 pricing**	**Difference in PV of Costs between 'existing scenario' and 'intervention scenario', lower-bound CO_2 pricing**	**Difference in PV of Costs between 'existing scenario' and 'intervention scenario', upper-bound CO_2 pricing**
[+]50% (INR 30/kg)	–152,107	–154,404	–156,065	–158,551	–3,958	–4,147
[+]40% (INR 28/kg)	–152,091	–154,388	–156,065	–158,551	–3,974	–4,163
[+]30% (INR 26/kg)	–152,075	–154,372	–156,065	–158,551	–3,990	–4,179
[+]20% (INR 24/kg)	–152,059	–154,356	–156,065	–158,551	–4,006	–4,195
[+]10% (INR 22/kg)	–152,043	–154,340	–156,065	–158,551	–4,022	–4,211
modeled (INR 20/kg)	**–152,027**	**–154,324**	**–156,065**	**–158,551**	**–4,038**	**–4,227**

Note: The difference in PV shows potential PV of costs savings for 1 km of constructed road when using recycled plastic instead of traditional road. These values show PV of economic costs that include CO_2 valuation.

Conclusions

The CEA results suggest that the use of recycled plastic in road construction seems to be economically justifiable. While the results of the CEA show that using recycled plastic in roads construction is likely to be a cost-efficient solution, obstacles to this technology might still exist. For example, the road construction industry does not observe the economic prices, including carbon valuation (CO_2 co-benefits). Instead, what the sector faces are financial prices. Therefore, it is likely that the industry must first see the financial rationale for using plastic roads to fully employ this technology. Where such financial viability is not present, but there exists a solid motivation to introduce this solution to correct an existing market failure (unused plastic waste), a set of incentives could be introduced (for example, offsetting mechanisms resulting in corporate tax cuts, environment-friendly inputs tracing, and geo-tagging brand building and marketing mechanisms).

The 'on-the-ground evidence' seems to point to the financial viability of plastic roads as the industry is already engaged in this activity. Since plastic roads are constructed in India, cost savings for using recycled plastic in road construction must already exist. One may then question why the use of recycled plastic in road construction is not employed uniformly. There might be multiple reasons for such status quo. First, to make sure that the construction of the plastic roads is feasible, there must exist a reliable plastic recycling value chain that delivers the necessary volume of standardized and ready-to-use plastic that can be employed in the road construction process. Second, recycled plastic must have competitive pricing to allow the financial viability of this technological solution. Also, the location of recycled plastic providers is essential as transport costs can add to the financial expenditures.[23] The asphalt plants operate 'in bulk'; therefore, it is likely that they will expect recycled plastic to be delivered in bulk, at competitive prices, with standardized quality, and with a high level of timing reliability. On the recycling companies' side, forward contracting with the road construction agency for delivery of recycled plastic would be a possible incentive as recycling companies could plan and adjust their production possibilities.

Recycled plastic is expected to face competitive uses and multiple markets. It is anticipated that recycling companies might face numerous markets for their plastic (for example, apparel and clothing industry, furniture, and so on). The plastic prices are likely to differ, and recyclers might prefer to cater to non-road constructing industries. The road construction industry may not be the best option for recycling companies as it is likely to require low (bulk) prices. Recycling companies might not have economies of scale sufficient to provide the road industry with cheap input, especially when recycled plastic needs to be transported long distances, which will increase costs. It is also expected that there might exist a need to introduce an online trading platform that will connect asphalt plants with plastic recycling companies and where forces of demand and supply will set prices for recycled plastic.[24] Also, bringing together the necessary policies and well-monitored plastic road construction quality standards seems like a condition sine qua non. Lastly, well-designed incentivization schemes might need to be created for the road construction industry and plastic recyclers to help ensure that both industries will be willing to help jointly make recycled plastic in road construction a mainstream technology.

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23 The estimated transport costs are INR 1.2–2 per 1 km assuming 8 tons of load to be transported (1 truckload). This is the minimum volume for transport under this pricing.

24 Based on interviews with Green Worms: http://greenworms.org/.

As global plastic waste continues to grow, stakeholders are exploring new options to use plastic waste as partial substitute for raw material. The use of plastic waste as a bitumen modifier in road construction, referred to here as 'plastic roads', is one option being explored. We reviewed the scientific literature, news articles, and patents; conducted a cost-effectiveness analysis; and interviewed representatives from private companies and independent, scientific researchers to determine the existing knowledge gaps regarding the (1) technology feasibility, including engineering performance; (2) environmental issues; (3) occupational health; (4) economic viabilty; and (5) industry standards surrounding plastic roads. We found that many companies are starting to implement or pilot this technology worldwide though key gaps in engineering performance, such as cracking resistance, remain. The environmental issues reviewed also have research gaps, including the generation of hazardous air pollutants during production; microplastics and nanoplastics generation during use; and leaching of additives from plastic waste during use. Industry standards for the use of plastic waste in road construction are lacking. In addition, there is prevailing uncertainty in the economic viability of the technology. As a result of these key research gaps, the Way Forward section presents a roadmap for short-term and long-term research priorities.

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