The Incorporation of Plastics in Asphalt: A Review

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ABSTRACT: As the most versatile and innovative material, plastic's main sectors are packaging, construction, and automotive. Global plastic production is causing overflow in landfills, oceans, and the natural environment. The need to mitigate plastic pollution is imperative for the existence of various species on the planet as plastic production is to exceed 1300 million metric tons in 2050. One of the remedial methods to mitigate plastic pollution is to incorporate plastic in roadways, causing a global reduction in bitumen demand, material costs, and waste quantities. With over 2.5 and 3.2 million miles of asphalt roads in the United States and Europe, repurposing 5% of plastic waste in roadways can reduce 10-15% of global plastic pollution. This paper provides a literature review on the successful incorporation of plastic waste in roadways. By highlighting research conducted globally, this research presents an innovative solution to feasibly manage waste.

1 INTRODUCTION

Plastic is one of the most versatile and innovative materials. Created by Leo Henricus Baekeland in 1907, the first plastic, known as Bakelite, was a synthetic polymer made from phenol and formaldehyde (Baekeland 1909). Since plastic's creation, this material has composed innumerable products because of its favorable qualities. This polymeric compound has long hydrocarbon structures, making it extremely durable and easy to manufacture. Due to these long polycyclic and polymeric compounds, plastic takes a long time to degrade and decompose. Utilized in packaging and construction, plastic serves as a sterile, lightweight, and easy way to package and transport goods (Plastics Europe 2018). Research published in 2015 estimates that of the 6300 million metric tons produced, only 9% was recycled with 12% incinerated and 79% collecting in landfills or the environment (Geyer et al. 2017). Due to this issue, plastic disposal is of high importance.

Different solutions, such as improving product circularity, using conversion technology, and creating trackable smart bins, have been proposed to reduce waste quantities (Keller 2019). Incorporating plastics within public infrastructure can mitigate its pollution while promoting recycling. In fact, some cities are recognizing the importance of improving plastic recycling efforts. In 2017, the city of Boston released an ordinance regarding the cutback of plastic bags with the goal of jumpstarting the city's new zero waste initiative (O'Malley & Wu 2017; City of Boston 2019). It was estimated 393 kilotons(kt) of carbon came from managing municipal solid waste in 2017 (City of Boston 2019). Later that same year, China announced a new policy ban that will stop the county's import of plastic waste. As the leading global importer of plastic waste, at almost 106 million metric tons collected since 1992, this policy is expected to offset an estimated 111 million metric tons of waste by 2030 (Brooks et al. 2018).

One solution to repurpose soaring plastic waste quantities is its incorporation within construction materials. With over 2.5 and 3.2 million miles of paved asphalt roads in the United States and Europe, repurposing plastic into asphalted roadways could drastically improve public infrastructure (NAPA & EAPA 2011). Infrastructure affects a country's foundation and ability to have a prosperous economy. In the American Society of Civil Engineer's 2017 Infrastructure Report Card, America's cumulative infrastructure received a D+, with roadways receiving a D due to crowding and poor condition (Infrastructure Report Card 2017). It is estimated that for every 5 miles of highway pavement, 1 mile requires maintenance and rehabilitation, causing a suggested annual 6.9 billion hours and $160 billion in wasted time and fuel (Infrastructure Report Card 2017). If plastic waste is used in roadways as a replacement to bitumen, global plastic pollution and cost will drastically decrease while road quality, public safety, and nationwide resilience will increase.

While the idea of incorporating plastic into construction products may seem innovative, it is not a new concept. In fact, plastic incorporation within highways has already been experimented in countries such as India, Australia, Britain, Netherlands, and Indonesia (Economist 2018). In India, plastic is used to fill potholes and incorporated into asphalt mixtures, where test roads have shown promising results. In Australia, Netherlands, and Indonesia, test stretches have been completed in small scale tests. Within the Netherlands, a bike track was made from prefabricated, modular sections that incorporated recycled plastic within asphalt. In Britain, plastic mixes roads show promising results by not needing as much resurfacing maintenance as traditional roadways. All of these test models show the feasibility of incorporating plastics into roadways, with many declaring these construction projects to be of national importance (Lombardo 2018).

2 PLASTIC TYPES & COMMON USES

When reviewing plastic's composition, this polymeric material is made of elements such as carbon, hydrogen, and nitrogen, and has a high molecular weight that can copy the properties of natural materials (American Chemistry Council 2005). Two different types of plastics, thermoplastics and thermosets, devise numerous products used across various sectors. Thermoplastics, or plastics that can melt when heated or harden when cooled, show adaptable characteristics that allow for reworking. Thermosets, or plastics that experience a change in molecular structure, cannot be altered after achieving final form. Common thermoplastics include Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET) and Polyvinyl Chloride (PVC) and Polystyrene (PS). Common thermosets include Polyurethane (PUR), epoxy resins, and silicone. The most commonly used plastics include PP, PE, and PET, as these materials predominantly devise food packaging, plastic bags, and water bottles (Plastics Europe 2018).

When plastic debris ends up in oceans rather than landfills, these products often turn into microplastics. Microplastics are defined as plastic particles between 1 and 1000 micrometers that easily pollute natural environments because of their small nature (GESAMP 2015). It is anticipated that these plastics are a result of fragmentation from larger plastic waste, or physical degradation from weathering (Barnes et al. 2009). As a result, larger quantities of primary and secondary microplastics pose threats to the marine wildlife. The physical characteristics of plastic determine pollutant impact, a detrimental concern to the marine ecology. Among many characteristics, density and chemical structure determine the fate of microplastics. Density and its relativity to seawater decides buoyancy and final location, while chemical structure dictates how a microplastic will eventually oxidize and degrade (Andrady 2017). Despite being practically invisible to the naked eye, microplastics show the growing necessity to better manage plastic waste.

In 2015, it was estimated that of 6300 million metric tons produced, only 9% had been recycled, with 12% being incinerated and 79% collecting in either landfills or the environment (Geyer et al. 2017). The materials being recycled are predominantly PP and PE and come from the packaging and building and construction sectors (Plastics Europe 2018). To improve the circular life cycle of plastic, some end of life alternatives include mechanical reuse, product repair, or energy recovery. Mechanical reuse and product repair show promising results that allow plastic to be converted. In Europe, it is estimated that of the 51.2 million metric tons collected for conversion demand, the packing (39.7%), building and construction (19.8%), automotive (10.1%), and electrical and electronic (6.2%) sectors compose more than 75% of recycled materials (Plastics Europe 2018). Although plastic recycling has increased by almost 80% in the last ten years, there is still more progress to be made to reduce plastic pollution (Plastics Europe 2018). It is possible that by incorporating plastics within asphalt in roadways, recycling quantities can be further increased.

3 ASPHALT PROCESSES & MIX DESIGN

Asphalt, also known as bitumen, is a derivative of petroleum crude oil. This viscous material is made of carbon, hydrogen, and oxygen, and tends to have a low molecular weight. This material is often found in reservoirs that require extraction from the ground. To upgrade product quality, the thick fluid requires extreme heat through the refining process. Typically, bitumen can be created into intricate chemical mixtures that can produce different characteristics, an ability that makes it useful in the construction industry where specific properties are required (NAPA & EAPA 2011). Approximately 85% of all bitumen is used as a binder in asphalt for high ways, roads, parking lots, and foot paths (Afework et al. 2018). In 2007, it was estimated that approximately 1.6 trillion metric tons of asphalt were produced worldwide in a single year (NAPA & EAPA 2011). In the United States, it is suggested that 2,500 asphalt mixing sites produce a combined 350 million tons of asphalt pavement every year (NAPA 2011).

To create asphalt, aggregates are combined with bitumen to create Hot Mix Asphalt (HMA). This asphalt is mixed at high temperatures, typically ranging from 150^{o} C to 175^{o} C, at hot mixing plants. Because of high production temperatures, the asphalt has homogeneity between mixture components, creating good workability. However, these high temperatures also produce greenhouse gas emissions such as carbon dioxide, sulfur dioxide, volatile organic compounds (D'Angelo et al. 2008). These mixes are often used for roads and highways. Over an extended service lifespan, it is assumed that the asphalt will meet the needs of varying traffic and environmental conditions.

Traditional asphalt mix designs incorporate aggregates and bitumen, with some mixes also including Portland Cement. Some studies included fly ash in addition to filler, and both coarse and fine aggregates (Tiwari & Rao 2017). Local limestone is often used as the crushed material for both coarse and fine aggregates, with sieve analyses completed to understand the gradation composition (Celauro et al. 2019; Costa et al. 2017). Research even suggested using ophite as an additional aggregate and filler, while another study included black crushed gravel as aggregate and mixed the dust with sand to create filler (Vila-Cortavitarte et al. 2018; Jan et al. 2017). Overall, a well-made mix design is typically rated for resistance to deformation, moisture, fatigue, skid, and cracking.

Although this is the traditional process involved in making asphalt, a variety of specialty applications are being explored to find more environmentally friendly methods. For example, Warm Mix Asphalt (WMA) represents a new technology in which asphalt mixes are created at temperatures about 10 to 75 C lower than traditional mixtures (Mallick & El-Korchi 2017. This lower temperature is possible due to lowered viscosity of the asphalt binder, which can occur through modification to the traditional mix design through additives. As a result, these mixtures improve workability and compaction while reducing permeability (D'Angelo et al. 2008). Some additional benefits of WMA include reduced emissions, fuel usage, and worker exposure. This new method has evident environmental components, as there is a reduction in consumed natural resources, energy usage and production of carbon dioxide, resulting in a fuel savings of 20-35% (D'Angelo et al. 2008). With WMA, paving can be completed in temperatures lower than traditional asphalt, allowing for quicker pavement periods. Research indicates that WMA should be an allowable alternative to HMA.

In general, there are two different processes used for modifying bitumen mixtures with plastic: wet and dry. The dry process varies the aggregates while the wet process varies the bitumen. The wet process involves mixing shredded plastics directly with bitumen at high temperatures. This blended mixture allows the asphalt to withstand temperature and soaking conditions higher than that of the normal mixture, while having the advantage of incorporating any type of waste material (Gawande et al. 2012). However, this method often requires additional equipment and waiting time, as cooling is needed to avoid air pockets (Gawande et al. 2012). One study that used the wet process was able to conclude that 6% of plastic improved the bitumen mixture (Tiwari & Rao 2017). Other studies preferred this method for its ability to prevent additional additive costs (Moghaddam et al. 2013; Appiah et al. 2017).

In the dry process, aggregates are chosen, based on qualities such as adsorption, soundness, and porosity, and coated with a softened plastic. This coating improves the nature of the aggregate by decreasing porosity. Other advantages involve ease of method, improved binding properties, and no emission of toxic gases (Gawande et al. 2012). One publication even found that it feasible to incorporate higher percentages of plastic waste, with 10% of bitumen replaced with waste plastic, through the dry method (Vasudevan et al. 2012). Another modified dry process includes adding unheated plastic to heated aggregates for 30 seconds before adding fine aggregates and bitumen (Vila-Cortavitarte et al. 2018). The dry process is often selected for its simplicity and product homogeneity (Usman & Masirin 2019). Regardless of the process, both the wet and dry methods show that improved resistance to permanent deformation and fatigue resistance is possible with plastic modified asphalt mixtures (Costa et al. 2017).

4 ASPHALT PROCESSES & MIX DESIGN

To create these modified mixtures, a variety of plastics have proven effective when combined with bitumen. Research in Malaysia compared waste and virgin plastics and discovered that, when blended to form a modified bitumen mixture, waste polymer mixtures too showed improved physical properties (Kalantar et al. 2012). Some of the most common waste plastics combined with asphalt include PE, covering Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE) and Cross-Linked Polyethylene (PEX), PET, PP, and PS. These types of plastics derive from products such as plastic bags, wrappers, films, water bottles, electrical cables and hangers. Other materials, such as cold-in place recycled foam asphalt, crumbed rubber, and stabilized bottom ashes, have also been researched in asphalt mixtures (Kim et al. 2009; Khan et al. 2016; Topini et al. 2018).

To be incorporated into asphalt mixtures, plastics are cut or shredded into strips, typically ranging from 1 to 4 mm (Vasudevan et al. 2012; Nkanga et al. 2017; Kalpana & Surendaran 2018; Tiwari & Rao 2017;

Appiah et al. 2017; Jan et al. 2017; Moghaddam et al. 2013). One study even shredded PET into strips of 0.78 mm by 10 mm to create a fiber-like materials (Usman & Masirin 2019). In other research, plastic was ground into flakes or pelletized before addition to the asphalt mixture (Costa et al. 2017; Melbouci et al. 2014; Celauro et al. 2019; Vila-Cortavitarte et al. 2018).

While the mixing process involved does alter the amount of plastic incorporated, many of these mixes included proportions of plastic, by weight of bitumen, within 0% to 15% (Nkanga et al. 2017; Kalpana & Surendaran 2018; Tiwari & Rao 2017; Khan et al. 2016). Some studies used even finer proportions of plastic, within 0% to 3% of waste material, by weight of bitumen (Appiah et al. 2017; Usman & Masirin 2019; Vila-Cortavitarte et al. 2018). However, one publication used even bolder increments, varying plastic in 5% increments from 55 to 20% plastic, by weight of bitumen (Vasudevan et al. 2012).

After these modified plastic asphalt mixtures are created, a variety of tests are conducted to assess the properties. To better understand bitumen, it is important to know the safety, age hardening, and temperature susceptibility of the material (Mallick & El-Korchi 2017). Tests, such as penetration (ASTM D5), specific gravity (ASTM D70), and ring and ball softening point (NA 2617), can provide information about binder properties such as penetration grade, mass ratio, and softening point (Mallick & El-Korchi 2017; Melbouci et al. 2014; Jan et al. 2017).

To evaluate waste plastic characteristics, analysis includes water adsorption (ASTM D570), strain (ASTM C1557), specific gravity (ASTM D792), grading curve (EN 993-1), and particle density (EN 1097-6) (Usman & Masirin 2019; Costa et al. 2017). These tests, when conducted on waste plastic, provide a more in depth understanding of material performance, size, and density. When using the wet method, the characteristics of plastic coated aggregate can be evaluated through moisture adsorption (AASHTO T96), soundness (AASHTO T96), aggregate impact (AASHTO T 96), and Los Angeles abrasion (AASHTO T96) (Vasudevan et al. 2012). These tests assess the aggregate's resistance to weathering, toughness, and abrasion.

After understanding the different materials involved, it is crucial to assess the overall modified plastic asphalt mixture. One of the most popular tests is the Marshall Stability (ASTM D1559; EN 12697-34), which provides information on asphalt stability, indicating the modified pavement's capacity to withstand load (Vasudevan et al. 2012; Melbouci et al. 2014; Nkanga et al. 2017; Moghaddam et al. 2013; Jan et al. 2017). Other common tests include bitumen extraction (ASTM D2172), indirect tensile (ASTM D4123 or EN 12697-23), rutting resistance (EN 12697-22), fatigue resistance (EN 12697-24), and stiffness modulus (EN 12697-26) (Vasudevan et al. 2012; Nkanga et al. 2017; Usman & Masirin 2019; Costa et al. 2017; Celauro et al. 2019; Vila-Cortavitarte et al. 2018; Moghaddam et al. 2013). These tests present data regarding the mixture's bonding nature, material quality, deformation, and bearing capabilities. One study even used Fourier transform infra-red (FTIR) technology to examine chemical changes occurring during the mixing of waste plastic with asphalt (Appiah et al. 2017).

This plethora of tests helps to analyze the properties of the bitumen, plastic, and the combined plastic asphalt. Findings from a host of research indicates that not only will incorporating waste plastic into asphalt help reduce plastic pollution, but also improve characteristics and performance. Bettered characteristics of plastic modified mixtures include water repellence, material binding, and decreased density (Jan et al. 2017; Appiah et al. 2017; Vasudevan et al. 2012; Costa et al. 2017). Improved physical properties include durability, fatigue resistance, performance life, deformation resistance, and strength (Tiwari & Rao 2017; Nkanga et al. 2017; Moghaddam et al. 2013; Usman & Masirin 2019; Celauro et al. 2019; Rahman & Wahab 2013; Jan et al. 2017; Melbouci et al. 2014).

5 CASE STUDIES

To further validate this literature review, two publications are used as case studies in evaluating the incorporation of asphalt within roadways. In Malaysia and India, research has been completed regarding this successful means of reducing plastic pollution. In Malaysia, green pavement was synthesized by incorporating PET from plastic water bottles within bitumen mixtures. In India, the dry method was utilized to incorporate a variety of waste plastics in an eco-friendly method. This source shows the successful evaluation and implementation of plastic roads.

According to research published by Rahman and Wahab in Malaysia in 2013, PET can be used as a partial fine aggregate replacement. This PET, used in the form of recycled plastic pellets, was tested in 5% increments, by weight of the asphalt mixture, from 5% to 25%, while bitumen content was varied from 4% to 6%, by weight of the asphalt. A density-voids and resilient modulus analysis indicated that 5% of mass of the asphalt mixture was the optimum bitumen content. In combination with an 80/100 penetration grade bitumen, the bitumen and aggregate were compacted through a Marshall Compactor, and the replacement pellets were added to the mix.

The samples were subjected to tests, such as Repeated Load Axial Test (RLAT) and Indirect Tensile Stiffness Modulus Test (ITSM), to determine permanent deformation and stiffness. Testing results, as shown in Figure 1, indicate that the stiffness of recycled asphalt mixtures tends to be lower than that of unmodified asphalt mixtures. However, ITSM results show that the 20% PET asphalt mixture displayed remarkable deformation recovery even after 1800 loading cycles. As a result, it is possible that recycled PET, when used in asphalt, can improve asphalt properties, resist road failures, decrease bitumen quantities, and reduce road construction costs.

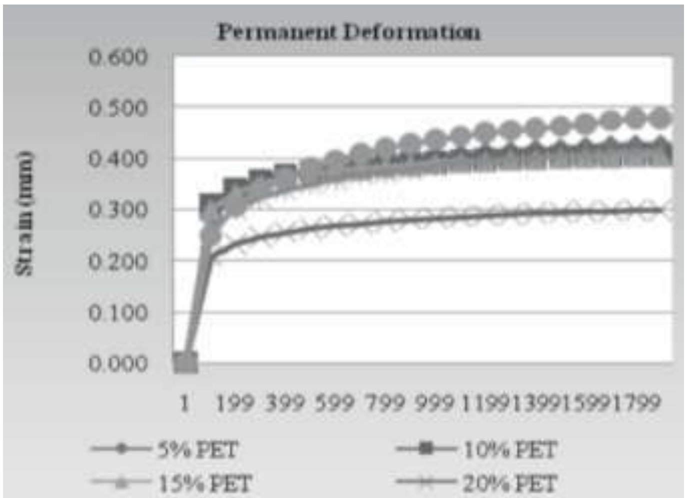


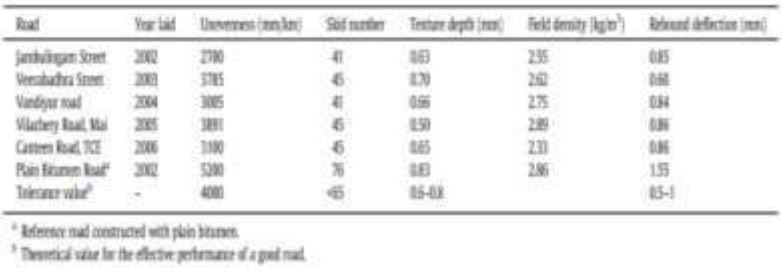
Figure 1. Graph of RLAT Results Assessing Permanent Deformation in Unmodified and Modified Asphalt Samples. Adapted from Rahman & Wahab (2013). Copyright 2013 by Procedia Engineering.

Research published by Vasudevan in India in 2012 shows that waste plastic is being disposed of in an ecofriendly way through its application to flexible pavements. This procedure takes advantage of the softening points of plastic, and heats rather than burns the material to avoid producing toxic gases. Known as the dry process, this method releases no carbon dioxide emissions, helping to avoid greenhouse gas emissions. It is estimated that for every 1 km, at least 1 metric ton of waste plastic is used, reducing carbon dioxide emission by at least 3 metric tons.

Waste plastics are shredded between 2.5mm and 4.36 mm and heated to 170^o C. Shredded plastic waste is sprayed over the stone aggregate and then mixed with bitumen. This spraying method allowed for a higher percentage of plastic waste to be used without concern over material separation, producing a higher quality aggregate. The hot plastic-coated aggregate is evaluated for binding properties such as moisture absorption (AAHSTO T96), soundness (AAHSTO T96), aggregate impact (AAHSTO T96), and Los Angeles abrasion (AAHSTO T96). Results indicate that the modified asphalt experiences significant strength improvement, with enhanced properties from the plastic polymer coating.

To characterize physical properties, the modified mix was subjected to additional tests such as Marshall Stability (ASTM D:1559-1979), bitumen extraction (ASTM D2172) and stripping value (IS: 6241-1971). The Marshall value improved as the plastic coating filled and binded the aggregate with the bitumen. The Marshall Stability test upgraded by 50% to 60%, in comparison with the unmodified sample. Results also displayed that, when plastic coated aggregate was used, the required quantity of bitumen reduced by 0.5% of the total weight. This 0.5% reduction in total weight decreases the overall quantity of bitumen by 10%. The extraction test showed that removal of bitumen after the plastic coating was more difficult in comparison to the plain bitumen coated aggregate, indicating a successful blend of materials. In fact, the modified extraction was only able to be extracted after the sample was refluxed in an industrial solvent, decalin.

A field study analyzed six different sites to evaluate the performance of five plastic roads in comparison to one plain bitumen road. These sites were evaluated for deflection (IRC: 8101997), unevenness (IRC: SP16-2004), field density, skid resistance (ASTM E 303-83), texture depth (BS 598 Part 105), and surface condition. Results, as shown in Figure 2, indicate that these plastic roads, which were laid between 2002 and 2006 and surveyed between May 2007 and May 2008, performed much better than traditional asphalt roads.



Road	Year laid	Unevenness (mm/km)	Skid number	Texture depth (mm)	Field density (kg/m^3)	Rebound deflection (mm)
Jambulingam Street	2002	2700	41	0.63	2.55	0.85
Veerabadhra Street	2003	3785	45	0.70	2.62	0.68
Vandiyur road	2004	3005	41	0.66	2.75	0.84
Vilachery Road, Mai	2005	3891	45	0.50	2.89	0.86
Canteen Road, TCE	2006	3100	45	0.65	2.33	0.86
Plain Bitumen Road[a]	2002	5200	76	0.83	2.86	1.55
Tolerance value[b]	-	4000	<65	0.6–0.8		0.5–1

[a] Reference road constructed with plain bitumen.

[b] Theoretical value for the effective performance of a good road.

Figure 2. Summary of Field Study Results Analyzing Six Different Sites in India to Evaluate Performance of Plastic Roads (Sites 1-5) Compared with Plain Asphalt Road (Site 6). Adapted from Vasudevan et al. (2012). Copyright 2012 by Construction and Building Materials.

The Benkelman Beam test, used to understand deflection, indicated that the bitumen layer of the traditional road lost its visco elastic properties after extended exposure to the atmosphere. However, the modified plastic road experienced no changes to the visco elastic behavior within the same bitumen layer due to enhanced binding properties. Unevenness, measured using MERLIN equipment, was drastically different between the two roads. The plain bitumen road resulted in unacceptable levels of unevenness due to poor binding, disentangling of materials, and oxidation due to aging, while the plastic road showed continued uniformity due to strong bonding, helpful changes in bitumen structure, and increased stability. When analyzing field density over 7 years, the traditional road experienced a decreased performance of 19% while the plastic road experienced a reduction of 9% to 10%. Skid resistance and texture depth also improved for the plastic road in comparison to the traditional road. The surface condition survey showed that the plastic roads experienced no pot holes, cracking, rutting, or flaws within the road.

Both case studies prove the feasibility and importance of modifying traditional bitumen mixes with plastic. By repurposing waste plastic through Vasudevan’s patented dry process, flexible and sustainable pavement can be made through an ecofriendly method. As a result, this sustainable construction will reduce bitumen quantities, repurpose waste plastics, produce less greenhouse gas emissions, and reduce pavement costs.

6 CONCLUSION

As plastic production continues to increase exponentially, alternative methods to mitigate plastic pollution are imperative. Based on the literature review presented in this paper, findings suggest that the incorporation of plastic within roadways can serve as a remedial method to alleviate plastic’s detrimental effects to the environment. Not only will this addition repurpose waste products, but also reduce bitumen amounts, improve roadway characteristics, lower construction costs, diminish greenhouse gas emissions, and promote a circular economy. Further research and field tests are suggested to verify the findings in this paper. It has been estimated that if 5% plastic waste is used to replace bitumen in roadways, there will be a 10% to 15% decrease in global plastic pollution.

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