Clean Technologies and Recycling

Clean Technologies and Recycling, 3(1): 71–91.
DOI: 10.3934/ctr.2023005
Received: 09 January 2023
Revised: 02 March 2023
Accepted: 06 March 2023
Published: 22 March 2023

http://www.aimspress.com/journal/ctr

Mini review

Utilization of commodity plastic wastes in flexible pavement: A review

Wilson Uzochukwu Eze[1,*], Reginald Umunakwe[2], Michael Ifeanyichukwu Ugbaja[1], Mohammed Kabiru Yakubu[1,3], Narcillina Nkechi Adegboro[1], Amina Hassan Bayero[1] and Maryann Ifeoma Uzochukwu[1]

[1] Department of Polymer Technology, Directorate of Polymer and Environmental Technology, Nigerian Institute of Leather and Science Technology, Zaria, Kaduna, Nigeria
[2] Department of Metallurgical and Material Engineering, Federal University, Oye-Ekiti, Nigeria
[3] Department of Polymer and Textile Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria

* **Correspondence:** Email: wilstyrene@yahoo.ca.

Abstract: Plastics are not inherently bad, as it is what we do and what we do not do after use that really counts. Plastics are pleasant to the eye, light in weight, sleek to the touch, currently indispensable, relatively cheap and sustainable with good use. Because of these desirable properties, the use, demand and production of plastic goods for various applications are on a steady rise. Consequently, the volume of the corresponding waste is also on the rise due to the non-biodegradable nature of these petroleum-based plastics. Mechanical recycling, which is the widely employed recycling route, is not holistic because it only delays the time for the waste plastics to get to the dump site and litter the environment. The use of waste plastics in bituminous mixtures for road construction is an emerging sustainable route for most types of commodity plastic wastes. This paper reviews the progress, techniques, suitability and possible health and environmental risks of waste plastics for a flexible pavement system. SWOT analysis to highlight the advantages and disadvantages of plastic waste utilization in bituminous mix was also conducted and is reported here.

Keywords: plastic waste; bitumen; aggregates; plastic-modified bitumen; plastic-coated aggregates; toxic fumes

1. Introduction

Commodity plastics are plastics which are not expensive and do not possess any exceptional mechanical properties. Such plastics are produced in large volumes for various applications, such as food packaging and storage, household products, beverages and carry bags. These plastics are mostly utilized in the production of single-use plastic items. Consequently, their demand and production are on the steady rise, resulting in larger volumes of their waste in municipal solid waste streams, with many ending up in water bodies due to their light weight. According to the European Association of Plastics Manufacturers report of world thermoplastics demand by type for the year 2015 [1], commodity plastics production stands at 85% of total plastic production; as shown in Figure 1.

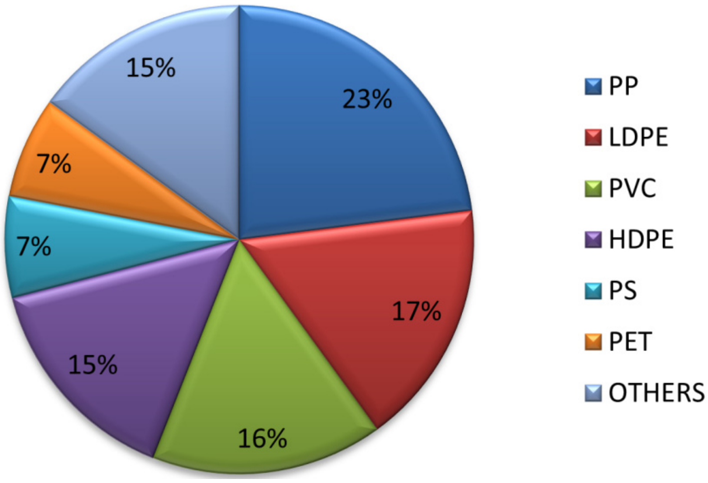

Figure 1. Production by volume of commodity plastics in 2015.

An estimated 6.3 billion tons of plastic waste has thus far been produced around the world, and only about 9% has been recycled. Another 12% has been incinerated, while the rest (79%) has been dumped into the environment [2]. Primarily, thermoplastics are recycled by using them to produce other items, usually of lesser value; this is termed mechanical recycling. This route has also presented challenges which have led it to achieving little in terms of eradicating the mountains of plastic waste in dumpsites. These challenges include the high cost of energy required to run the plastic processing machines and the cost of cleaning, sorting and disassembling, which eventually surpasses the cost of using virgin plastics [3].

Other recycling pathways for plastic waste, such as thermochemical processes; pyrolysis [4], fluid catalytic cracking [5], hydrogen techniques and gasification [6], have come with challenges that have hampered their acceptance. Such challenges include the immiscibility of polymer blends, huge cost of initial investment and high sulfur and chlorine contents of the pyrolysis fuel, which are beyond the acceptable limits for use in heat and power applications [7]. While thermochemical processes remain one holistic process of permanently taking plastic waste out of the environment, it is still not sustainable for now. Therefore, the urgent need for more holistic and viable pathways for plastic waste valorization is required now more than ever.

A quality road network is an indispensable type of infrastructure in developed and developing cities. Huge investments into road construction are being made in cities around the world with the aim of building roads that will last for decades. Fortunately, plastics are materials that endure in the environment for decades due to non-degradability. This quality, among others, makes them suitable materials for long-lasting components in flexible pavement construction.

The use of polymeric materials as modifiers in different layers for flexible pavement is not a new technology. Yildirim [8] reported that Thompson and Hoiberg were the first to employ the use of virgin polymers as modifiers for road construction as far back as 1843. Similarly, González et al. [9] reported an improvement in the bonding properties of bitumen/aggregate mixtures by incorporating plastics. Furthermore, the use of plastics as a partial replacement for bitumen was reported by Leng et al. [10]. In all of the above cited works, the idea was not to solve the problem of plastic waste in the environment; in most instances, virgin plastics were used, and not waste plastics.

One pathway that is gradually receiving the attention of researchers is the inclusion of some type of plastic waste as a modifier into the bituminous mixture (BM) for flexible pavement construction. This technology is still in its infancy, as only a few countries have commenced such experiments on roads of a few kilometers [11,12].

The utilization of suitable plastic waste as a modifier for aggregates or a partial replacement in bitumen is an alternative pathway for solving the problem of plastic pollution; it is a prospective new research focus that has huge potential to reduce the large volume of plastic waste generated in cities around the world, with possible improvement in the quality of road construction.

In this review, we present the trend of research progress for this technology based on the available literature. The review presents the suitable types of waste commodity plastics for BMs, the method of processing and effects of plastic waste/BM on the quality of flexible pavement, as well as health and environmental risks of some waste plastics used for bitumen modification.

2. Flexible pavement

Conventional flexible pavement is a built surface for roads, parking areas, railway tracks, ports and airport runways. Depending on the purpose and strength requirement, it may be composed of the following layers: surface layer, underlying base, sub-base courses and sub-grade layer (Figure 2). The surface layer is largely a mixture of aggregates and asphalt—also known as bitumen; it is a sticky, black, highly viscous liquid or semi-solid form of petroleum whose viscous nature allows significant plastic deformation. Most asphalt surfaces are built on a gravel base, although some entire surfaces are built directly on the sub-grade.

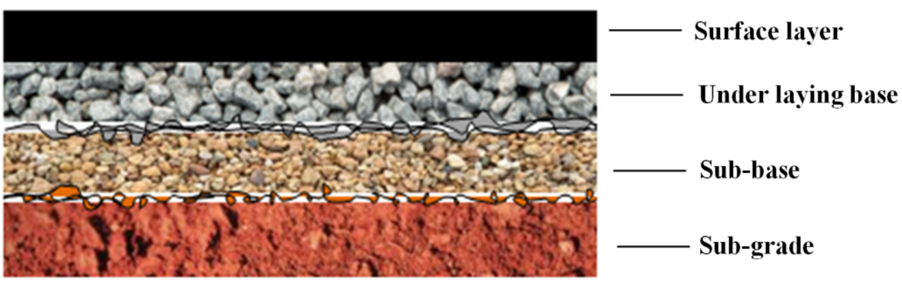

Figure 2. Cross section of the layer of flexible pavement.

Based on the temperature at which it is applied, asphalt is categorized as hot mix asphalt, warm mix asphalt or cold mix asphalt. However, the inclusion of waste plastics in bitumen as a modifier is suitable with the hot mix asphalt application technique. The surface layer is the layer directly in contact with the load, which transmits down to the sub-grade. This layer also interacts with the environmental elements, such as rain, heat from the sun and other elements resulting from human activity. Therefore, much attention to this surface is required, as failure and durability largely depends on it. Every layer has a specific role in the making of high-quality pavement, but this review is focused on the surface layer where the waste plastics are utilized.

3. Suitable waste plastic type

Plastics are broadly classified as thermosetting or thermoplastic; this classification is based on their response to heat after shaping. Thermoplastics are those with a reversible heat cycle, while thermosetting plastics have an irreversible heat cycle. The above thermal behavior is directly related to the structural makeup of the two classes of plastics. Thermoplastics have a third network structure which also promotes rigidity and usually makes them brittle; these properties make them unfit as a candidate for the modification of bitumen for flexible pavement construction.

Thermoplastics, on the other hand, are known to be more flexible and can also be reshaped several times by melting; therefore, they are able to form a coating on aggregates. They also hold aggregates together and are relatively flexible at elevated temperature which helps to reduce the cracking of flexible pavement. However, not all thermoplastic waste may be suitable for blending with bitumen because of the possible emission of harmful gases at elevated temperatures during processing and service; this is due to possible leaching into underground water [13,14]. Secondly, waste plastics for bitumen modification must be able to withstand the upper temperature limit of bitumen processing, which is about 200 °C without degrading. It is important to note that the volume and proportion of waste plastic types commonly found in municipal solid waste streams depends on a number of factors, which include the consumption pattern, locality and economic and purchasing power. Hence, commodity plastic wastes are mostly found in solid waste streams. They include packaging bags (low-density polyethylene, LDPE), table water and soft drink bottles (polyethylene terephthalate, PET), disposable plates (polystyrene, PS), bottle caps (high-density polyethylene, HDPE) and other articles made from polypropylene (PP).

The thermogravimetric analysis (TGA) of some commodity plastic wastes shows that they can withstand the upper processing temperature of BMs (Table 1).

Table 1. Non-isothermal TGA at heating rates of 5 °C/min for commodity waste plastics. PVC: polyvinyl chloride.

S/No	Plastic type	Decomposition unset (°C)	Reference
1	HDPE	421.85	Kayacan and Doğan [15]
2	LDPE	386.85	Kayacan and Doğan [15]
3	PP	300	Esmizadeh et al. [16]
		330	Miandad et al. [17]
4	PET	400	Miandad et al. [17]
5	PVC	270	Palmay et al. [18]

However, thermoplastic waste contains some additives, such as plasticizers, which are incorporated during secondary plastic processing [19], and volatile impurities [20]. These volatile fumes are potentially harmful when inhaled by humans, especially over prolonged or repeated exposure. Plasticizers have the potential to leach into the soil over time, which may contaminate water bodies and, by extension, harm humans, animals and the environment [13,14,21]. Therefore, bitumen/plastic processing technology that will minimize such fumes are recommended, as the next section will discuss.

Furthermore, a report by Vasudevan et al. [22], as summarized in Table 2, has shown that, even though thermoplastics such as LDPE, HDPE, PP and PS also have the potential to release gases like ethane and methane, they do so at temperatures above 270 °C, which is below the processing temperature of bitumen/plastic mixtures; this further supports their suitability for bitumen modification.

Table 2. Thermal properties of polymers.

Polymer	Solubility		Softening temperature range in, °C	Products reported	Decomposition temperature range, °C	Products reported	Ignition temperature range, °C	Products reported
	Water	EPT[a]						
PE	Nil	Nil	100–120	No gas	270–350	CH_4 C_2H_4	>700	CO, CO_2
PP	Nil	Nil	140–160	No gas	270–300	C_2H_6	>700	CO, CO_2
PS	Nil	Nil	110–140	No gas	300–350	C_6H_6	>700	CO, CO_2
PVC*					135–200	HCl		

[a]5% acetic acid. Source: Vasudevan et al. [22]; *https://oxoplast.com/en/stability-of-polyvinyl-chloride [23].

4. Commodity plastic waste-modified asphalt

4.1. PP waste-modified BM

PP waste has been reported by many researchers to be an excellent modifier for bitumen. It is usually added to bitumen to improve the quality of the surface layer of flexible pavement. Findings reported in the literature show that PP exhibited significantly higher effectiveness in terms of strength, durability and performance when used as a modifier in bituminous pavement.

Otuoze and Shuaibu [24] assessed the Marshall properties of high-density PP (HDPP) waste and its potential to mitigate pavement failure due to environmental and traffic loading. The results revealed enhanced engineering properties with 2% HDPP at an optimal bitumen content of 5.5%. They reported an improvement in the stability of the reduction in flow or ductility of the bituminous layer. Similarly, Chetan et al. [25] in their study on the utilization of industrial PP waste in the asphalt binder for flexible pavements, reported an increase in the specific gravity of the standard aggregate from 2.85 to 2.916 for 6% PP waste, and 3.071 for 10% PP waste. They also noted that the toughness of the aggregate increased. Generally, the modification of bitumen with PP waste reduces the ductility of the BM, which could be attributed to the structural makeup of PP. Properties such as water resistance and high-temperature performance were significantly improved [25].

4.2. HDPE waste-modified BM

The modification of bitumen with HDPE improves most Marshall properties, but its high crystallinity results in resistance to flow, high viscosity and high stiffness, which makes for poor creep recovery [26,27]. Hınıslıoğlu and Ağar [28] investigated the influences of different HDPE-modified binders obtained by varying the mixing time, mixing temperature and HDPE content on the Marshall stability and flow. They concluded that the sample prepared at a 165 °C mixing temperature and 30 min mixing time with 4% HDPE had the highest stability and the lowest flow; thus, it had the highest Marshall quotient and good rutting resistance. Nejad et al. [29] also reported a significant improvement in rutting resistance at 7% HDPE content.

4.3. LDPE waste-modified BM

The use of LDPE for bitumen modification gained significant acceptance due to its lower specific gravity, which arises from its long linear chain structure compared to HDPE. This amorphous structure is able to compact properly with the bitumen to improve rutting resistance and low-temperature performance. Lubis et al. [30] studied the effects of LDPE addition to the characteristics of asphalt mixture, they found that the addition of 6% LDPE was increasing the value of dynamic stability, decreasing the rate of deformation and increasing crack resistance.

4.4. PS waste-modified BM

The use of PS waste as a modifier for bitumen has been reported by numerous researchers. Reduction in the ductility of the BM is consistent with most reports in the literature [31–33]. When compared with LDPE, HDPE and PP, PS imparts brittleness into the BM, which makes it less suitable in cold climatic regions. However, the rutting resistance is significantly improved in PS-modified asphalt pavements. The decrease in ductility or flow resulting from the inclusion of PS waste is an indication of good rutting resistance [31].

4.5. PET waste-modified BM

PET has been successfully used to modify bitumen for flexible pavement, and it has been shown to result in good high-temperature performance, with characteristics such aslow susceptibility to cracking and deformation at high temperatures, improved rutting deformation resistance and increased fatigue resistance [34]. Due to the poor compatibility and stability of PET in bitumen, the composition of PET is kept as low as 12% in the Marshall mix [35,36].

4.6. Polyvinyl chloride waste-modified BM

The thermal decomposition of polyvinyl chloride (PVC) is associated with hydrogen chloride emission, which becomes obvious at 135 °C. Furthermore, in the presence of free oxygen, the liberated hydrogen chloride speeds up the polymer decomposition process so much that, at a temperature of 200 °C, a nearly total breakdown of PVC takes place.

Furthermore, chlorinated plastics such as PVC are the third most widely produced polymer, after polyethylene and PP. PVC comes in two basic forms: rigid PC and flexible PVC. The rigid form of PVC is used in the construction of pipes, and in profile applications such as doors and windows. It is also used for bottles and other non-food packaging applications such as identity cards. It can be made softer and more flexible by incorporating plasticizers such as phthalates during secondary processing. In this form, it is also used in plumbing, electrical cable insulation, leather alternatives, signage, inflatable products and many applications where it replaces rubber.

Unfortunately, its production, use and disposal create persistent toxic pollution, including dioxins [37], and heating PVC at high temperatures can cause dangerous chloride emissions into the atmosphere [38]. Dioxins are produced at many points in the making of PVC, and additional dioxins are produced if PVC burns, which can occur either during garbage incineration, in structural or automobile fires or during the preparation of bitumen/plastic mixtures for flexible pavement.

Workers involved in making PVC or its basic ingredients are exposed to vinyl chloride, a known human carcinogen [39–42], and chemicals from PVC production, such as lead [43] and phthalates [44], have contaminated the groundwater near several plants. Lead and other heavy metals are sometimes used as a stabilizer or to impart other properties to PVC plastic, and phthalates are used as plasticizers. Because of these additives, recycling is nearly impossible for most PVC products, and this interferes with the recycling of other plastics. Unfortunately, most researchers have reported the use of this plastic for flexible pavement, and construction industries are ignorantly using it for flexible pavement construction to the detriment of the health of their workers.

Shahin [45] studied the effect of soaking period on the compressive strength of compacted BMs with reclaimed polyethylene and reclaimed PVC. He reported that the addition of 10% reclaimed polyethylene increased the Marshall stability by 92% relative to pure bitumen. Otherwise, 7.5% (waste polyvinyl chloride) WPVC increased the Marshall stability by 76% relative to pure bitumen.

Rahman et al. [46] reported the use of waste WPVC pipes as a modifier in the construction of pavements in hot climates. They reported a significant improvement in the flow and stability of the BM. Again, the health risk associated with the toxic fumes was not considered in their research.

Li et al. [47] carried out research on the dual effect of calcium oxide on waste PVC plastic pyrolysis by performing a kinetics study using Fraser–Suzuki deconvolution. They reported that the inclusion of calcium oxide increased the activation energy of the process but lowered the release of hydrogen chloride gas. Acidic gases are not only harmful to humans, but they are also the major cause of acid rain. Their study has further validated the non-suitability of waste PVC for bitumen/plastic mixtures.

Similarly, Rahman et al. [48] conducted a performance evaluation for waste polyethylene and PVC in hot asphalt mixtures. They concluded that penetration, ductility and solubility of the modified asphalt mixture decreased with the increase of the polyethylene and PVC modifier. On the basis of the experimental stability, stiffness and void characteristics results, they found out that the asphalt mixtures with the waste polyethylene modifier at up to 10% and waste PVC modifier at up to 7.5% can be used for flexible pavement construction in a warmer region. However, like many other studies reported in the literature, their study did not include a thermal analysis of the feedstock to investigate the possible release of toxic fumes.

Table 3 shows a summary of the effects of each commodity plastic waste on asphalt, as reported by different researchers.

Table 3. Summary of the effects of each commodity plastic waste on asphalt.

S/No	Plastic waste	Properties	Optimum quantity (%wt)	References
1	LDPE	Improved strength, less voids, good flow	12	Rajput and Ydav [49]
		(34% decrease in flow value—an indication of good stability), improved rutting resistance	12	Dubey and Gupta [50]
2	HDPE	Improved rutting resistance		Dalhat and Al-Abdul Wahhab [51]
		Good Marshall stability, high Marshall quotient, good rutting resistance, good strength	4	Hınıslıoğlu and Ağar [28]
3	PP	Increased viscosity and softening point, improved rutting resistance		Dalhat and Al-Abdul Wahhab [51]
		Poor low-temperature performance, 5% of PP results in a 20% reduction of ductility		Al-Hadidy and Yi-qiu [52]
4	PS	Decreased penetrationand ductility and increased softeningand flash and firepoints	15	Abdulkadir and Ramazan [53] Baker et al. [54]
5	PET	Improved elastic and viscoelastic properties, decreased strain deformation	6	Moghaddam et al. [55]
		Improved rutting resistance, increased stiffness	4–6	Ahmadinia et al. [56]
6	PVC	Improved rutting and fatigue resistance, poor cracking resistance at low temperatures		Ziari et al. [57]

5. Plastic/bitumen processing techniques

The incorporation of plastic waste into bitumen for flexible pavement results in a modification of the properties of the bitumen. Three basic processes have been fully established: dry, wet and modified processes.

5.1. Wet process

The wet process of bitumen modification is a technique wherein a modifier (plastic waste) is added to bitumen (binder) and heated with simultaneous mixing until a proper melt and the desired mixing is achieved. Depending on the type of plastic involved, the mixing temperature is usually not less than 165 °C [58]. The thermal stability, melting temperature and thermal degradation of the plastic usually determine the process temperature.

The hot modified bitumen is now mixed with hot aggregate within the same temperature range of approximately 160–170 °C, while compaction of the aggregate/modified bitumen is done at a lower temperate of about 130 °C.

The quality of pavement made via the wet process can be determined by conducting tests such as the Marshall stability test, a wheel tracking test on the pavement and a viscosity test on the modified bitumen.

One major concern in the wet process is the exposure to the toxic fumes liberated during the mixing of the crushed plastics and the hot bitumen. The fumes may be a result of the breakdown of large plastic molecules into volatile compounds, as well as a result of volatile compounds from additives such as plasticizers, master batch and chlorinated plastics [59–61]. However, some researchers have reported that, in this process, during mixing, the plastic wastes absorb volatile compounds from the bitumen while the plastics are thermally degraded.

The wet process is controlled by some factors, such as the size of the crushed waste plastics, the duration of the bitumen/crushed plastic wastes in the mixing chamber and the melting temperature of the plastic. Waste plastics such as LDPE, HDPE and PP, which have melting temperatures below the processing temperatures of typical asphalt, are more suitable for use in wet processes as modifiers (or potential modifiers) in asphalt production. The wet process is depicted in Figure 3 below.

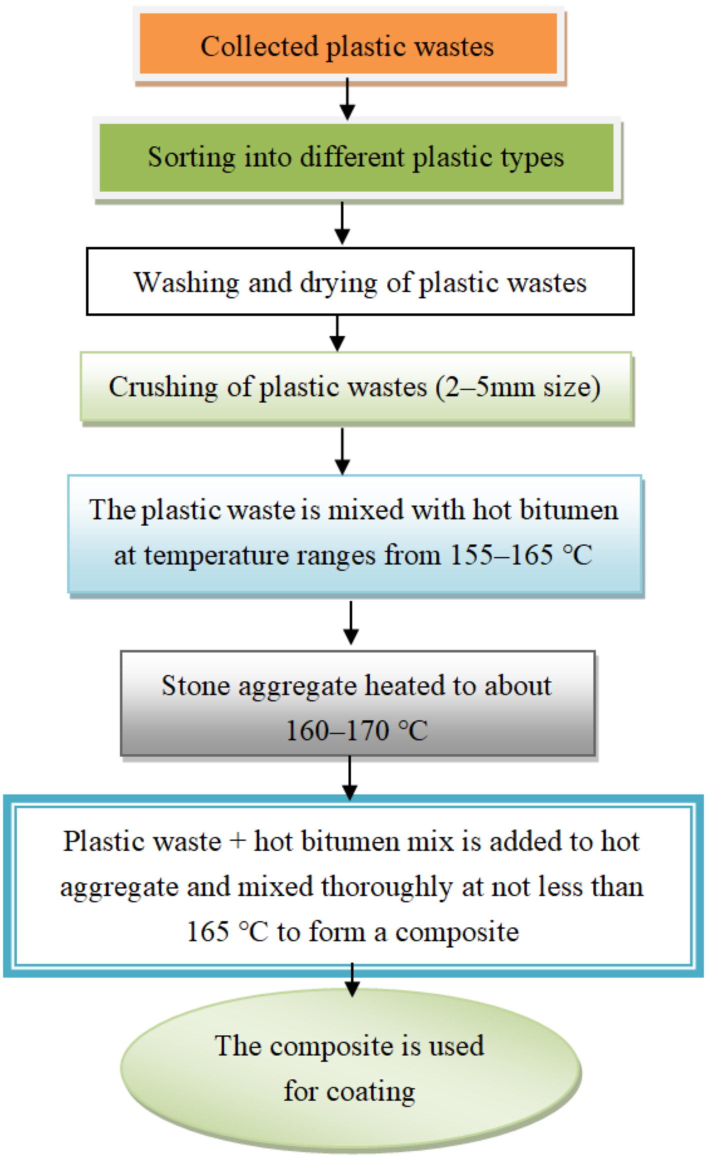

Figure 3. Flow diagram of the wet process.

5.2. Dry process

In this process, an appropriate quantity of dry crushed waste plastic is mixed with hot aggregate at a temperature between 165 and 170 °C until the plastics coats the aggregate uniformly. The bitumen is heated up to 160 °C prior to mixing with the plastic-coated aggregate. The resulting composite is sustained at 130–140 °C for laying on the road [62]. Figure 4 shows the schematic diagram of the dry process.

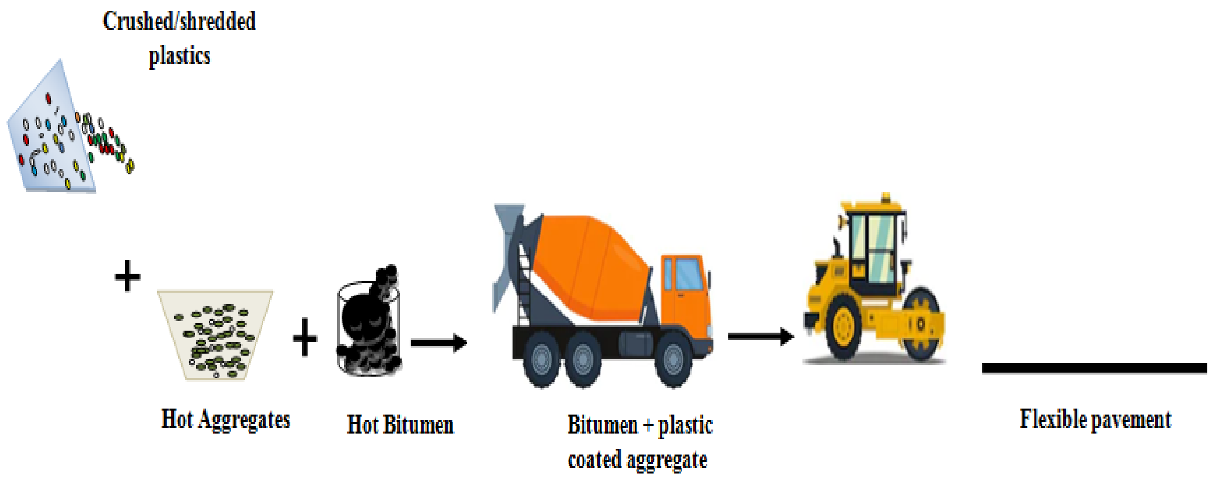

Figure 4. Schematic representation of the dry process.

The dry process offers a number of advantages over the wet technique; for instance, it is relatively cheap, as it requires less equipment and less labor; it also favors the consumption of more of the waste plastics. However, poor interaction between the bitumen and modifier (plastic wastes) is often a major setback in this process [63]. Waste plastics such as PET and PS are more suitable for dry process modification because of their high melting temperatures.

5.3. Modified process

The modified process is a non-conventional technique that addresses the shortfalls in the wet and dry processes. The wet process is the first technique employed by researchers and construction industries. However, the liberation of potential harmful fumes is a major health concern, as has been explained in the previous sections. Second, the energy demand associated with stirring the bitumen/waste plastic mixtire is also a challenge. On the other hand, in the dry process, the short interaction time between the bitumen and plastic-coated aggregate creates the problem of binder/modifier compatibility. Researchers have reported various techniques that can overcome these challenges, and this has led to the modified process. The modification process is therefore a technique that is based on the wet or dry process with a modification that could address some of the following problems: improve the compatibility between waste plastics and bitumen, suppress the release of potential toxic fumes, chemical treatment of the plastic waste to improve some of the Marshall properties through better interaction between the plastics and bitumen, etc.

Radeef et al. [64] identified inconsistent performance in pavement constructed via the dry process due to poor interaction with the binder and improper distribution of the plastic waste particles in the mixture skeleton. They attributed these inconsistencies to an inaccurate mixing method, the shredding size, the mixing temperature and ingredient priorities. Hence, they used a modified dry process to address these shortfalls. Their modified dry process was intended to ensure high digestion of the thin melted layer on the aggregate by using the asphalt binder. To achieve this, they reported a three-step procedure; the first step includes heating the coarse aggregate (>3.35 mm) to a temperature of 180 ± 5 °C before gradually adding the shredded plastics to the aggregate. The second step is to properly mix for 4 min to ensure that the plastic particles had melted and coated the aggregate. The final step is mixing the plastic-coated aggregate with a portion of the optimal aggregate content (17% of the total weight of asphalt content, 5%) for 2 min.

Jalal [65] used a chemical additive to overcome the poor interfacial relationship between the bitumen and plastic modifier. They treated the modifier with dichromate and sulfuric acid, while the bitumen was treated with a cross-linking agent (polyethylenimine). They reported a marked improvement in retained stiffness after water immersion testingas compared with the untreated samples.

6. Some characterization techniques for bitumen/plastic blends

6.1. Marshall stability and flow test (ASTM D6927-06)

The Marshall method of asphalt mix design is widely practiced in construction materials laboratories to select and proportion aggregate and asphalt materials for pavement construction that give the optimum density that meets the required stability and flow. The Marshall stability method developed by Bruce Marshall at the Mississippi Highway Department in 1939 seemed to be the most promising after adding a procedure to measure deformation (flow). The Marshall test is extensively employed by construction industries for paving jobs. The stability of the mix is defined as a maximum load carried by a compacted specimen at a standard test temperature of 60 °C, while the flow is measured as the deformation in units of 0.25 mm between no load and the maximum load carried by the specimen during the stability test (the flow value may also be measured by deformation units of 0.1 mm) [66]. The Marshall stability test is helpful to get the optimum binder content for the aggregate mix type, as well as traffic intensity. The Marshall test has been used by many researchers to determine the optimum blend ratio of bitumen/waste plastics in BM composition [67–69].

6.2. Wheel tracking test (BS 598-110 and EN 12697-22)

Rutting is a type of permanent deformation of pavements that occurs under the wheel path in contact with the surface layer as a result of a poor BM or heavy traffic loads on the road. Laboratory wheel-tracking devices are used to run simulations that measure mixture asphalt quality by rolling a small loaded wheel device repeatedly across a prepared asphalt specimen [70]. This test has been conducted by researchers to evaluate and determine the resistance of the waste plastic-modified bitumen blends to rutting [71–73].

6.3. Water absorption tests

Aggregates are ranked on the basis of the moisture absorption capacity. The preferred aggregate for flexible pavement is to possess low water absorption capacity. One of the advantages of including waste plastics in asphalt mixtures is being able to harness the water absorption resistance inherent to petro-plastics. The aggregate coated with plastics has been reported to have a better quality of flexible pavement in terms of moisture absorption [71,72]. The effects of various types of plastic waste/bitumen blends on the water absorption of flexible pavement has been studied and reported [72,73].

6.4. Specific gravity (ASTM D2726)

This test is useful to calculate the percentage of air voids in the compacted dense modified asphalt mixes. The specific gravity of a compacted mixture is determined by using the water displacement method. The specific gravity provides an indirect measure of the strength of the flexible pavement sample. It has been reported that the higher the specific gravity, the higher the strength of the pavement. Radeef et al. [72] in their study on the use of plastic waste along with bitumen in the construction of flexible pavement, reported an improvement in the strength of polyethylene and PP waste-modified bitumen with a higher specific gravity.

7. SWOT analysis of utilizing commodity plastic wastes as a modifier in bitumen for flexible pavement construction

SWOT analysis is an assessment tool which analyzes the information of a system or plan in terms of its strengths, weaknesses, opportunities and threats. Although strengths and weaknesses are linked to immediate advantages and disadvantages of utilizing waste plastics in BM, opportunities and threats are linked to potential positive and negative implications of utilizing waste plastics in BM. The SWOTs were obtained from extensive reports on the utilization of plastic waste in flexible pavement construction (Figure 5).

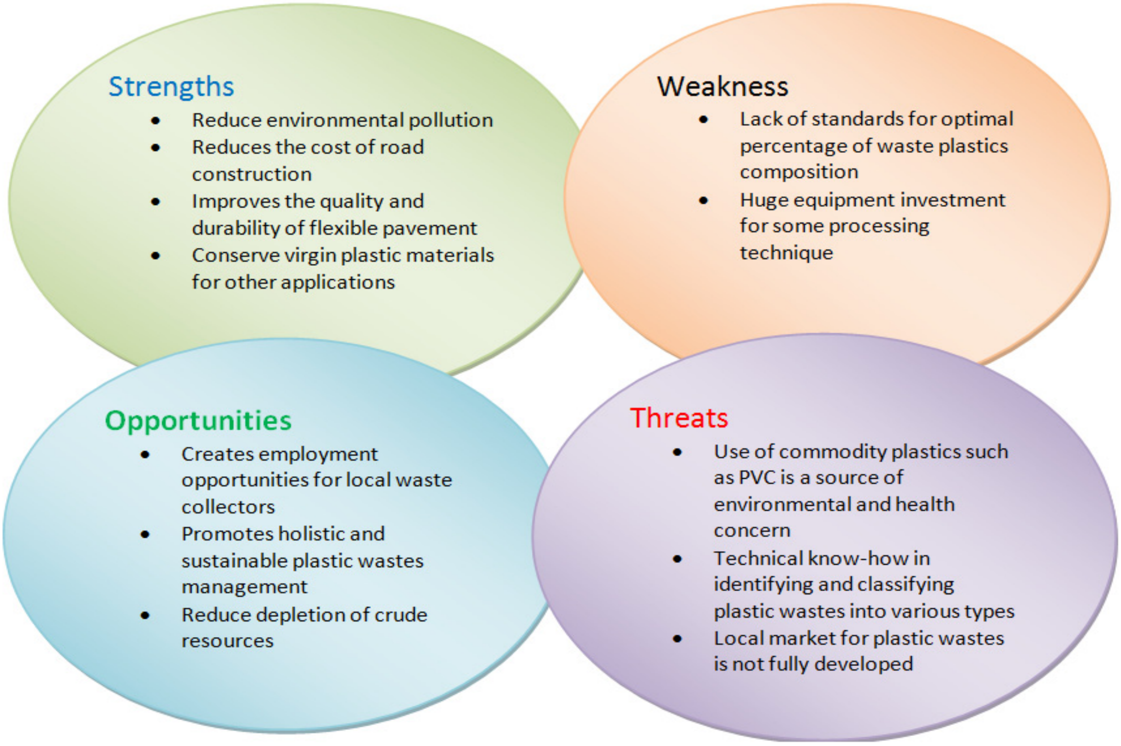

Figure 5. Graphical presentation of SWOT analysis.

7.1. Strengths

7.1.1. Reduce environmental pollution

The utilization of a huge volume of commodity plastic waste, most of which come from single-used plastics, will reduce the burden of solid waste on the environment. The utilization of waste plastics in flexible pavement represents a sustainable pathway for environmental conservation and a reduction of the negative effects of plastic pollution on humans, animals and the ecosystem [74].

7.1.2. Reduce the cost of road construction

The substitution of some of the bitumen with plastic waste in flexible pavement construction has the potential to significantly reduce the cost associated with bitumen purchase, thereby reducing the overall cost of road construction since discarded plastics are deemed as waste; thus, they are estimated to have little to no value. Therefore, the use of such materials for construction purposes will eliminate the cost associated with conventional building materials and reduce the overall cost of construction.

7.1.3. Improve the quality and durability of flexible pavement

Studies on the use of plastic wastes as modifiers in bitumen for flexible pavement construction have shown exciting results regarding the performance of the pavement samples. Improvement in the key properties was recorded for different types of plastic materials. The improvements in moisture and water resistance reported by Suaryana et al. [71] and Radeef et al. [72] will ultimately improve the life span of the road.

7.1.4. Conserve virgin plastic materials for other applications

Earlier modification of BMs was done using virgin plastics [8,10], with the intention to improve the performance of the bitumen. Today, plastic wastes are used to realize improvements such asthe conservation of virgin materials for other top-notch purposes where purity is of importance.

7.2. Weaknesses

7.2.1. Lack of standards for optimal percentage of waste plastic composition

Different types of plastics have different chemical and structural makeups, which determine their properties. There is no standardized optimum percentage of plastic waste required by standard regulatory authorities for laid Marshall mixtures. To this end, standardization is still a major challenge.

7.2.2. Huge equipment investment for some processing techniques

Specifically, the wet and modified processes are associated with huge equipment investments to achieve proper mixing of the plastics and bitumen. This tends to pose a challenge, especially for smaller construction companies.

7.3. Opportunities

7.3.1. Creates employment opportunities for local waste collectors

The use of plastic waste in rod construction will place a demand on the material which, in turn, will provide employment opportunities for local waste collectors and for those who work in preparation centers, were washing, sorting and shredding activities are done.

7.3.2. Promotes holistic and sustainable plastic waste management

Unlike secondary recycling, upcycling and downcycling, which only delays the time for plastic waste to return to the environment and dump sites, the use of plastic waste for road construction ensures that these materials are completely eliminated from the waste stream. As such, they represent a sustainable pathway toward achieving the goal of a circular economy.

7.3.3. Reduce the depletion of crude resources

When used and discarded, plastics are reused to serve the purpose of the modification of bitumen in place of virgin plastics; thus, the demand for the virgin materials for the purpose of road construction will be drastically reduced.

7.4. Threats

The emission of toxic fumes resulting from heating PVC at elevated temperatures is an issue of health and environmental concern. Furthermore, the technical know-how required for the identification of such plastics in the stream of comingled recycling demands that workers are given special training to avoid it. To this end, workers may be exposed to health problems if safety is not assured. Finally, in order for road construction companies to have ready access to large volumes of plastic waste, there is a need for a market with standardized price; this will happen when the demand is placed on waste plastics.

8. Strategies and action plans for future usage of plastic waste to enhance the sustainability for flexible pavement construction

The use of plastic waste as a modifier or partial replacement for bitumen has shown to be efficient in improving the quality of flexible pavement, consequently presenting a viable option for reducing the volume of waste plastics in the environment. However, the technology has not received adequate attention by construction industries, possibly due to a number of factors which include, but are not limited to, the following:

i. Inadequate and poor implementation of incentives on deposit-refund schemes
ii. Technological know-how
iii. Lack of plastic waste banks
iv. Lack of long-term data on the performance of waste plastic-modified pavements.

Strategic action plans to enhance the utilization of these wastes in flexible pavement must address the points listed above. This can be achieved through the following strategies:

(1) In a deposit–refund system, consumers pay deposits that are added to the price of a product, and they receive refunds when they return the used products [59]. Plastics, which include beverage containers, batteries and automobile tires, are used in this scheme. These schemes can be effective in boosting the collection rates and the establishment of plastic waste banks, as well as curtailing plastic waste littering in the environment. Unfortunately, these schemes have not been adopted by most underdeveloped and developing nations. Developed countries [59–61] have implemented container deposit schemes which make for easy collection of these wastes for various recycling routes.

(2) Technological know-how, which included the knowledge of the identification, classification and sorting of various plastics for their suitability, or otherwise for flexible pavement, is still a key challenge in deploying the technology of waste plastic-modified bitumen. To this end, construction companies need to engage plastic professionals as part of their technical manpower.

(3) Lack of plastic waste banks where waste can be accessed readily is a major challenge for these technologies. There is need for countries to invest in the local collection and sorting of plastic wastes to divert these wastes from landfills. Governments need to deliberately develop standards and

policies to strengthen the demand for plastic waste, which will naturally create a market with better incentive.

(4) Lack of long-term data on the performance of waste plastic-modified pavements is one factor that has hampered the speed of adoption of this technology. The transition from research to practice is still at an early stage and needs much more research. Specifically, research efforts should be geared toward demonstrating that incorporating recycled plastics has no negative impact on the long-term performance, life-cycle costs, environmental impact and recyclability of asphalt pavements, or any unintended consequences on the health and safety of the plant operators and construction crews provided that the appropriate plastic type and technology are employed. Furthermore, low-risk demonstration projects are needed to identify the potential changes in the production and construction practices of asphalt mixtures containing recycled plastics.

9. Conclusions

The use of waste polymers for modifying asphalt has remarkable environmental and economic advantages. Many researchers have evaluated the use of plastic waste as a modifier for bitumen, concluding that this material could be more attractive and economical than the usual polymer modifiers. However, the safety and health concerns due to the possible release of potential poisonous fumes by some types of plastics have not been reported. Most reports focus on the optimum quantity of plastic waste used and property evaluation, without a critical characterization of the plastic waste in terms of the possible toxicity of fumes emitted during the high-temperature process. Based on this review on the modification of asphalts with commodity plastic waste, the following points can be drawn:

i. LDPE, PP, HDPE and PET have shown to be excellent materials with good thermal stability within the processing temperature of bitumen for flexible pavement construction.
ii. The wet processing method can be adequately used for LDPE, HDPE and PP incorporation into BMs since no potential harmful fumes are emitted within the processing temperature range of these wastes using these methods. Second, their melting temperatures are within the processing temperature range of bitumen.
iii. The dry processing method can be adequately used for PS and PET incorporation into BMs because of their high melting temperatures.
iv. PVC may be used as a modifier in BMs, but they are not suitable for the wet and dry processes due to the liberation of dangerous fumes. However, modified processes wherein a chemical substance is included to suppress the emission of toxic fumes from the PVC may be a future research focus.

Acknowledgments

The Nigerian Institute of Leather and Science Technology (NILEST) is acknowledged.

Conflict of interest

The authors declare no conflict of interest.

References

1. Plastics Europe, Association of Plastics Manufacturers, World Thermoplastics Demand by Types 2015. Plastics Europe, 2015. Available from: https://plasticseurope.org/wp-content/uploads/2021/10/2015-Plastics-the-facts.pdf.
2. Hira A, Pacini H, Attafuah-Wadee K, et al. (2022) Plastic waste mitigation strategies: A review of lessons from developing countries. *J Dev Soc* 38: 336–359. https://doi.org/10.1177/0169796X221104855
3. Eze WU, Madufor IC, Onyeagoro GN, et al. (2021) Study on the effect of Kankara zeolite-Y-based catalyst on the chemical properties of liquid fuel from mixed waste plastics (MWPs) pyrolysis. *Polym Bull* 78: 377–398. https://doi.org/10.1007/s00289-020-03116-4
4. Eze WU, Umunakwe R, Obasi HC, et al. (2021) Plastics waste management: A review of pyrolysis technology. *Clean Technol Recy* 1: 50–69. https://doi.org/10.3934/ctr.2021003
5. Ajibola AA, Omoleye AJ, Efeovbokhan VE (2018) Catalytic cracking of polyethylene plastic waste using synthesized zeolite Y from Nigerian kaolin deposit. *Appl Petrochem Res* 8: 211–217. https://doi.org/10.1007/s13203-018-0216-7
6. Saad JM, Williams PT (2016) Catalytic dry reforming of waste plastics from different waste treatment plants for production of synthesis gases. *Waste Manage* 58: 214–220. https://doi.org/10.1016/j.wasman.2016.09.011
7. Fulgencio-Medrano L, García-Fernández S, Asueta A, et al. (2022) Oil production by pyrolysis of real plastic waste. *Polymers* 14: 553. https://doi.org/10.3390/polym14030553
8. Yildirim Y (2007) Polymer modified asphalt binders. *Constr Build Mater* 21: 66–72. https://doi.org/10.1016/j.conbuildmat.2005.07.007
9. González O, Peña JJ, Muñoz ME, et al. (2022) Rheological techniques as a tool to analyze polymer−bitumen interactions: Bitumen modified with polyethylene and polyethylene-based blends. *Energy Fuels* 16: 1256–1263. https://doi.org/10.1021/ef020049l
10. Leng Z, Sreeram A, Padhan RK, et al. (2018) Value-added application of waste PET based additives in bituminous mixtures containing high percentage of reclaimed asphalt pavement (RAP). *J Cleaner Prod* 196: 615–625. https://doi.org/10.1016/j.jclepro.2018.06.119
11. Appiah JK, Berko-Boateng VN, Tagbor TA (2017) Use of waste plastic materials for road construction in Ghana. *Case Stud Constr Mater* 6: 1–7. https://doi.org/10.1016/j.cscm.2016.11.001
12. Babu KK, Raji AK (2007) Utilization of marginal materials as an ingredient in bituminous mixes: Highway research record. *IRC* 36: 42–43.
13. Magdouli S, Daghrir R, Brar SK, et al. (2013) Di 2-ethylhexylphtalate in the aquatic and terrestrial environment: a critical review. *J Environ Manag* 127: 36–49. https://doi.org/10.1016/j.jenvman.2013.04.013
14. Wang J, Luo Y, Teng Y, et al. (2013) Soil contamination by phthalate esters in Chinese intensive vegetable production systems with different modes of use of plastic film. *Environ Pollut* 180: 265–273. https://doi.org/10.1016/j.envpol.2013.05.036
15. Kayacan, Doğan ÖM (2008) Pyrolysis of low and high density polyethylene. Part I: Non isothermal pyrolysis kinetics. *Energy Sources Part A* 30: 385–391. https://doi.org/10.1080/15567030701457079

16. Esmizadeh E, Tzoganakis C, Mekonnen TH (2020) Degradation behavior of polypropylene during reprocessing and its biocomposites: Thermal and oxidative degradation kinetics. *Polymers* 12: 1627. https://doi.org/10.3390/polym12081627
17. Miandad R, Rehan M, Barakat MA, et al. (2019) Catalytic pyrolysis of plastic waste: Moving toward pyrolysis based biorefineries. *Front Energy Res* 7: 27. https://doi.org/10.3389/fenrg.2019.00027
18. Palmay P, Puente C, Barzallo D, et al. (2021) Determination of the thermodynamic parameters of the pyrolysis process of post-consumption thermoplastics by non-isothermal thermogravimetric analysis. *Polymers* 13: 4379. https://doi.org/10.3390/polym13244379
19. Dimitrov N, Krehula LK, Siročić AP, et al. (2013) Analysis of recycled PET bottles products by pyrolysis-gas chromatography. *Polym Degrad Stabil* 98: 972–979. https://doi.org/10.1016/j.polymdegradstab.2013.02.013
20. Dzieciol M, Trzeszczynski J (2000) Volatile products of poly (ethylene terephthalate) thermal degradation in nitrogen atmosphere. *J Appl Polym Sci* 77: 1894–1901. https://doi.org/10.1002/1097-4628(20000829)77:9<1894::AID-APP5>3.0.CO;2-Y
21. Fu X, Du Q (2011) Uptake of di-(2-ethylhexyl) phthalate of vegetables from plastic film greenhouses. *J Agr Food Chem* 21: 11585–11588. https://doi.org/10.1021/jf203502e
22. Vasudevan R, Ramalinga A, Sundarakannan B, et al. (2012) A technique to dispose waste plastics in an ecofriendly way—Application in construction of flexible pavements. *Constr Build Mater* 28: 311–320. https://doi.org/10.1016/j.conbuildmat.2011.08.031
23. Segment Oxoplast, Stability of poly (vinyl chloride). Segment Oxoplast, 2015. Available from: https://oxoplast.com/en/stability-of-polyvinyl-chloride/.
24. Otuoze V, Shuaibu AA (2017) An experimental study on the use of polypropylene waste in bituminous mix. *Niger J Technol* 36: 677–685. https://doi.org/10.4314/njt.v36i3.3
25. Chetan Y, Khanapure VU, Joshi VP, et al. (2017) Utilization of industrial polypropylene (PP) waste in asphalt binder for flexible pavements. *Int Res J Eng Technol* 4: 2011–2016.
26. Costa LMB, Silva HMRD, Oliveira JRM, et al. (2013) Incorporation of waste plastic in asphalt binders to improve their performance in the pavement. *Int J Pavement Res Technol* 6: 457–464.
27. Punith PS, Veeraragavan A, Amirkhanian SN (2011) Evaluation of reclaimed polyethylene modified asphalt concrete mixtures. *Int J Pavement Res Technol* 4: 1–10.
28. Hınıslıoğlu S, Ağar E (2004) Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. *Mater Lett* 58: 267–271. https://doi.org/10.1016/S0167-577X(03)00458-0
29. Nejad V, Gholami M, Naderi K, et al (2014) Evaluation of rutting properties of high density polyethylene modified binders. *Mater Struct* 48: 3295–3305. https://doi.org/10.1617/s11527-014-0399-z
30. Lubis AS, Muis ZA, Siregar NA (2020) The effects of low-density polyethylene (LDPE) addition to the characteristics of asphalt mixture. *IOP Conf Ser Earth Environ Sci* 476: 012063. https://doi.org/10.1088/1755-1315/476/1/012063
31. Murana AA, Akilu K, Olowosulu AT (2020) Use of expanded polystyrene from disposable food pack as a modifier for bitumen in hot mix asphalt. *Niger J Technol* 39: 1021–1028. https://doi.org/10.4314/njt.v39i4.7
32. Nciri N, Shin T, Cho N (2020) Towards the use of waste expanded polystyrene as potential modifier for flexible road pavements. *Mater Today Proc* 24: 763–771. https://doi.org/10.1016/j.matpr.2020.04.384

33. Fang C, Jiao L, Hu J, et al. (2014) Viscoelasticity of asphalt modified with packaging waste expended polystyrene. *J Mater Sci Technol* 30: 939–943. https://doi.org/10.1016/j.jmst.2014.07.016
34. Mashaan NS, Chegenizadeh A, Nikraz H, et al. (2021) Investigating the engineering properties of asphalt binder modified with waste plastic polymer. *Ain Shams Eng J* 12: 1569–1574. https://doi.org/10.1016/j.asej.2020.08.035
35. Ahmad MS, Ahmad SA (2022) The impact of polyethylene terephthalate waste on different bituminous designs. *J Eng Appl Sci* 69: 53. https://doi.org/10.1186/s44147-022-00104-5
36. Ogundipe OM (2019) The use of polyethylene terephthalate waste for modifying asphalt concrete using the Marshall test. *Slovak J Civil Eng* 27: 9–15. https://doi.org/10.2478/sjce-2019-0010
37. Zhou S, Liu C, Zhang L (2019) Critical review on the chemical reaction pathways underpinning the primary decomposition behavior of chlorine-bearing compounds under simulated municipal solid waste incineration conditions. *Energ Fue* 34: 1–15. https://doi.org/10.1021/acs.energyfuels.9b02958
38. Chong NS, Abdulramoni S, Patterson D, et al. (2019) Releases of fire-derived contaminants from polymer pipes made of polyvinyl chloride. *Toxics* 7: 57. https://doi.org/10.3390/toxics7040057
39. Haley JT (2009) Vinyl chloride: How many unknown problems? *J Toxicol Environ Health* 1: 47–73. https://doi.org/10.1080/15287397509529308
40. Kielhorn J, Melber C, Wahnschaffe U, et al. (2000) Vinyl chloride: still a cause for concern. *Environ Health Persp* 108: 579–588. https://doi.org/10.1289/ehp.00108579
41. Kohn MC, Parham F, Masten SA, et al. (2000) Human exposure estimates for phthalates. *Environ Health Persp* 108: 440–442. https://doi.org/10.1289/ehp.108-a440b
42. Gennaro V, Ceppi M, Crosignani P, et al. (2008) Reanalysis of updated mortality among vinyl and polyvinyl chloride workers: Confirmation of historical evidence and new findings. *BMC Public Health* 8: 1–8. https://doi.org/10.1186/1471-2458-8-21
43. Tilley SK, Fry RC (2015) Priority environmental contaminants: understanding their sources of exposure, biological mechanisms, and impacts on health, In: Fry RC, *Systems Biology in Toxicology and Environmental Health*, Amsterdam: Academic Press, 117–169. https://doi.org/10.1016/B978-0-12-801564-3.00006-7
44. Ohlson CG, Hardell L (2000) Testicular cancer and occupational exposures with a focus on xenoestrogens in polyvinyl chloride plastics. *Chemosphere* 40: 1277–1282. https://doi.org/10.1016/S0045-6535(99)00380-X
45. Shahin M (2016) *Effect of Water on the Compressive Strength of Bituminous Mixes*, Saarbrucken: LAP Lambert Academic Publishing.
46. Rahman ZU, Abbas A, Ahmad I, et al. (2021) Suitability of waste poly-vinyl-chloride (PVC) pipes as a modifier in the construction of pavements in hot climates. *Sir Syed Univ Res J Eng Technol* 10: 49–52. https://doi.org/10.33317/ssurj.226
47. Li X, Tang Y, Zhao Y, et al. (2022) Dual effect of CaO on waste PVC plastics pyrolysis: A kinetics study using Fraser–Suzuki deconvolution. *Thermochim Acta* 715: 179295. https://doi.org/10.1016/j.tca.2022.179295

48. Rahman MN, Ahmeduzzaman M, Sobhan MA, et al. (2013) Performance evaluation of waste polyethylene and PVC on hot asphalt mixtures. *Am J Civ Eng Archit* 1: 97–102. https://doi.org/10.12691/ajcea-1-5-2
49. Rajput PS, Yadav RK (2016) Use of plastic waste in bituminous road construction. *Int J Sci Technol Eng* 2: 509–513.
50. Dubey P, Gupta N (2019) Utilization of low density plastic waste in construction of flexible pavement with a partial replacement of bitumen. *Int J Res Appl Sci Eng Tech* 7: 1989–1996. https://doi.org/10.22214/ijraset.2019.4362
51. Wahhab HIAA, Dalhat MA, Habib MA (2016) Storage stability and high-temperature performance of asphalt binder modified with recycled plastic. *Road Mater Pavement Des* 18: 1117–1134. https://doi.org/10.1080/14680629.2016.1207554
52. Al-Hadidy AI, Yi-qiu T (2009) Mechanistic approach for polypropylene-modified flexible pavements. *Mater Design* 30: 1133–1140. https://doi.org/10.1016/j.matdes.2008.06.021
53. Abdulkadir K, Ramazan D (2009) A new technique of processing for waste-expanded polystyrene foams as aggregates. *J Mater Process Tech* 209: 2994–3000. https://doi.org/10.1016/j.jmatprotec.2008.07.017
54. Baker MB, Abendeh R, Abu-Salem Z, et al. (2016) Production of sustainable asphalt mixes using recycled polystyrene. *Int J Appl Environ Sci* 11: 183–192.
55. Moghaddam TB, Soltani M, Karim MR (2014) Evaluation of permanent deformation characteristics of unmodified and polyethylene terephthalate modified asphalt mixtures using dynamic creep test. *Mater Design* 53: 317–324. https://doi.org/10.1016/j.matdes.2013.07.015
56. Ahmadinia E, Zargar M, Karim MR, et al. (2012) Performance evaluation of utilization of waste polyethylene terephthalate (PET) in stone mastic asphalt. *Constr Build Mater* 36: 984–989. https://doi.org/10.1016/j.conbuildmat.2012.06.015
57. Ziari H, Nasiri E, Amini A, et al. (2019) The effect of EAF dust and waste PVC on moisture sensitivity, rutting resistance, and fatigue performance of asphalt binders and mixtures. *Constr Build Mater* 203: 188–200. https://doi.org/10.1016/j.conbuildmat.2019.01.101
58. Sahu AK, Singh RK (2016) Application of waste plastic materials in road construction. *2nd International Seminar On "Utilization of Non-Conventional Energy Sources for Sustainable Development of Rural Areas"*, Bhilai, India, 1–5.
59. Daisuke N (2009) Economic analysis of deposit–refund systems with measures for mitigating negative impacts on suppliers. *Resour Conserv Recy* 53: 199–207. https://doi.org/10.1016/j.resconrec.2008.11.008
60. Roca M, Ayuso S, Bala A, et al. (2022) Evaluating the implementation of a packaging Deposit and Refund System in Catalonia. Two surveys on citizenship's expected behaviour. *Sci Total Environ* 806: 150640. https://doi.org/10.1016/j.scitotenv.2021.150640
61. Roca M, Puigvert I, Ayuso S, et al. (2020) What factors determine attitudes towards the implementation of a packaging deposit and refund system? A qualitative study of the perception of Spanish consumers. *J Environ Manage* 270: 110891. https://doi.org/10.1016/j.jenvman.2020.110891
62. Rashid GMH, Tabassum A, Mahfuj R (2021) A review report on the utilization of plastic wastes in road construction. *J Transp Syst* 6: 1–8.
63. Nemade N, Prashant VT (2013) Utilization of polymer waste for modification of bitumen in road construction. *Sci Rev Chem Comm* 2: 198–213.

64. Radeef HR, Abdul HN, Abidin ARZ, et al. (2021) Enhanced dry process method for modified asphalt containing plastic waste. *Front Mater* 8: 700231. https://doi.org/10.3389/fmats.2021.700231
65. Jalal JJ (2016) Utilisation of waste plastic in bituminous mix for improved performance of roads. *KSCE J Civ Eng* 20: 243–249. https://doi.org/10.1007/s12205-015-0511-0
66. Dhanusha T, Madihu O, Abhishek VB, et al. (2019) Study on properties of BC mix by adding carbon black powder and E-waste. *Int Res J Eng Technol* 6: 3633–3637.
67. Gusty S, Tumpu M, Parung H, et al. (2021) Characteristics of porous asphalt containing low density polyethylene (LDPE) plastic waste. *IOP Conf Ser Earth Environ Sci* 921: 012025. https://doi.org/10.1088/1755-1315/921/1/012025
68. Mashaan NS, Chegenizadeh AH, Nikraz H (2022) Evaluation of the performance of two Australian waste-plastic-modified hot mix asphalts. *Recycling* 7: 16. https://doi.org/10.3390/recycling7020016
69. Zoorob SE, Suparma LB (2000) Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). *Cem Concr Compos* 22: 233242. https://doi.org/10.1016/S0958-9465(00)00026-3
70. Morea F, Zerbino R (2015) Wheel tracking test (WTT) conducted under different standards. Study and correlation of test parameters and limits. *Mater Struct* 48: 4019–4028. https://doi.org/10.1617/s11527-014-0460-y
71. Suaryana N, Nirwan E, Ronny Y (2018) Plastic bag waste on hot mixture asphalt as modifier. *Key Eng Mater* 789: 20–25. https://doi.org/10.4028/www.scientific.net/KEM.789.20
72. Radeef HR, Hassan NA, Katman HY, et al. (2022) The mechanical response of dry-process polymer wastes modified asphalt under ageing and moisture damage. *Case Stud Constr Mater* 16: e00913. https://doi.org/10.1016/j.cscm.2022.e00913
73. Kumar R, Khan MA (2020) Use of plastic waste along with bitumen in construction of flexible pavement. *Int J Eng Res Technol* 9: 153–158. https://doi.org/10.17577/IJERTV9IS030069
74. Kumar R, Verma A, Shome A, et al. (2021) Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* 13: 9963. https://doi.org/10.3390/su13179963