Closing the Loop

Harnessing Waste Plastics for Sustainable Asphalt Mixtures – A Comprehensive Review

Kumar Ashish, Prabin; Sreeram, Anand; Xu, Xiong; Chandrasekar, Pavan; Jagadeesh, Ajayshankar; Adwani, Dheeraj; Kumar Padhan, Rabindra

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Review

Closing the Loop: Harnessing waste plastics for sustainable asphalt mixtures – A comprehensive review

Prabin Kumar Ashish [a,*], Anand Sreeram [b], Xiong Xu [c], Pavan Chandrasekar [d], Ajayshankar Jagadeesh [e], Dheeraj Adwani [f], Rabindra Kumar Padhan [g]

[a] Dept. of Civil Engineering, Indian Institute of Technology Kanpur, Uttar Pradesh 208016, India
[b] Department of Engineering, University of Cambridge, UK
[c] School of Civil Engineering and Architecture, Wuhan Institute of Technology, Wuhan 430073, China
[d] Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta 30332, USA
[e] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Delft 2628CD, Netherlands
[f] Civil Architectural and Environmental Engineering, The University of Texas at Austin, TX 78712, USA
[g] Research and Development Centre, Indian Oil Corporation Limited, Faridabad, India

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ABSTRACT

The widespread production and consumption of plastics is a pressing global issue that requires multifaceted approaches and solutions. In terms of recycling, one of the ways to repurpose waste plastics in the construction industry would be to utilize them for asphalt pavement-related applications. Although this approach can potentially provide a value-added recycling outlet for plastics, several challenges need to be resolved to maximize its usage to the highest possible extent. Based on this, the present review article provides a comprehensive background on the different pertinent aspects associated with the use of waste plastics in asphalt mixtures. Besides examining the mechanical performance of asphalt mixtures containing waste plastic, the associated environmental concerns and life cycle assessment related attributes are also thoroughly deliberated. In addition, the successful demonstration of this technology through field trials in several countries is also discussed. Some of the main challenges related to the use of plastics in asphalt mixtures include the variability of plastic properties and composition, which can influence its mechanical performance and associated environmental impact. In general, the incorporation of waste plastics using certain tailored approaches can adequately meet and even enhance the typical performance parameters of asphalt mixtures. However, the effect of plastics modified asphalt mixtures on fuming and microplastics release remains unclear and needs further research. Nevertheless, the increasing number of field trials and widespread interest from transportation agencies around the world indicate the likelihood for the adoption of this technique as a sustainable practice in the pavement industry.

1. Introduction

Although plastics have several benefits and applications in different areas, their wide-scale consumption in the last couple of decades has created serious concerns for the environment. The lack of suitable disposal techniques, combined with the accumulation of waste plastic over the years, has led to an unprecedented crisis where it pollutes natural water bodies, overflows solid waste disposal landfills, as well as transmits carcinogenic fumes due to uncontrolled burning [1]. Therefore, waste plastics are among the major solid wastes that require recycling to the highest possible extent [2–3]. Unfortunately, the recycling rates of plastics around the world are substantially low. For example, the waste plastic recycling rate in the United States of America was consistently below 10% until 2019 [4]. Hence, an imperative need exists to find alternate recycling routes and outlets for waste plastics. Fortunately, along with various engineering-based applications, the use of waste plastic has gotten considerable attention in the construction industry (e.g., bricks, cement concrete roads, asphalt concrete roads, cementitious mortar composites). In this context, this review article focuses on the utilization of waste plastic in pavement-related applications, particularly for asphalt mixtures.

Besides the sustainability and solid waste management aspects, the use of waste plastics in asphalt mixtures is largely dictated by the changes it brings to its mechanical properties under different traffic and

* Corresponding author.
E-mail address: pkashish@iitk.ac.in (P.K. Ashish).

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environmental loading conditions. Moreover, due to the varying physical and chemical properties, different waste plastics hold unique challenges and must be addressed for their successful application in asphalt mixtures. Therefore, considerable attention is needed from the mechanical performance perspective (along with associated challenges and solutions) for its utilization to the highest possible extent. Furthermore, the release of potentially carcinogenic fumes during construction and the leaching of waste plastic particulates and associated toxic chemicals during the pavement service life are additional serious environmental and health concerns. Hence, focusing on the environmental and health-related concerns with the use of waste plastic in asphalt mixtures is equally important. Lastly, assessing Life Cycle Assessment (LCA) related attributes becomes essential from sustainability and long-term road construction perspectives.

Significant research efforts have been made in the recent past to evaluate the potential application of waste plastics in asphalt mixtures. Although several research works have been conducted to evaluate the mechanical performance of asphalt mixtures containing waste plastics, the information on other critically important attributes such as the significant challenges, environmental impact, LCA, field-based projects/trials have not been concisely reported, and the existing information is also highly scattered. For example, although the review article by Ma et al. [5] and Wu and Montalvo [6] extensively covered the discussion on the mechanical performance of asphalt mixtures containing waste plastics, the related discussion on environmental and health-related concerns was missing. Moreover, discussion on LCA and field-related projects was also minimal. Similarly, the review articles on this topic by Xu et al. [7] and Noor and Rehman [8] did not consider environmental and health-related concerns, LCA and field trials. Likewise, Sasidharan et al. [9] did not touch upon the environmental and LCA-related aspects of asphalt mixture containing waste plastics. In a similar direction, the review article by Abdy et al. [10] exclusively focused on the pyrolysis-based treatment of waste plastics for its potential application in asphalt mixtures without reflecting on their environmental, health, and LCA part. Overall, it is a challenge for readers to comprehend the holistic potential of waste plastic utilization in asphalt paving applications, especially because aspects other than mechanical performance, as mentioned above, hold critical consideration for sustainable and meaningful use in the field. Hence this article presents a comprehensive review of various aspects involved in the potential application of waste plastics in asphalt mixtures.

Overall, the scope of this article is as follows: (a) challenges and solutions for the utilization of waste plastics in asphalt mixtures, (b) the influence of waste plastics on the mechanical performance of asphalt mixtures, (c) environmental and safety concerns, (d) LCA and economic analysis, and (e) associated field trials in different countries. This review article is expected to be helpful for researchers, engineers and policy-makers as a reference guide to understand the current state-of-the-art information on this topic and accelerate the utilization of waste plastics in the field.

2. Challenges and solutions for waste plastics utilization in asphalt mixtures

2.1. Main challenges

The plastics family encompasses thousands of different materials with unique characteristics, properties, and uses. Broadly, plastics can be divided into thermoplastics and thermosets based on their chemical structure and change in different properties after heating. Thermoplastics, such as Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET), Polystyrene (PS), Polycarbonates (PC), and Acrylonitrile Butadiene Styrene (ABS) are a group of plastics that can be melted when heated and hardened when cooled [11] (Fig. 1). Likewise, thermosets are a group of plastics that undergo a chemical change when heated and create a three-dimensional network. Once processed, these plastics cannot be remelted and reformed for other usages. Examples of thermosets include Polyurethane (PU) and Epoxy Resins (ER) [12].

As of now, literature in this area is mostly related to the recycling of thermoplastics as modifiers due to their repeatable processing characteristics [13–15]. However, regarding thermosets, some studies have suggested that their reutilization as functional modifiers in asphalt mixtures is not easy. The best way to repurpose these plastics is through the mechanical processing approach, including crushing and grinding [16]. Though some of these waste plastics have shown the potential to be used in asphalt mixtures, many challenging issues still need to be considered, such as its high melting temperature, poor stability, and poor low-temperature cracking resistance.

As per the literature, the suggested production and implementation conditions and engineering properties of waste plastic-modified asphalt binders and mixtures incorporating various thermoplastics and thermosets are completely different and varied [10,17–18]. Some major characteristics and challenges in adopting these plastics for asphalt mixture based application are summarized in Table 1. It is believed that the first approach for waste plastic utilization in asphalt mixture should be the clear recognition of their category and material-related attributes

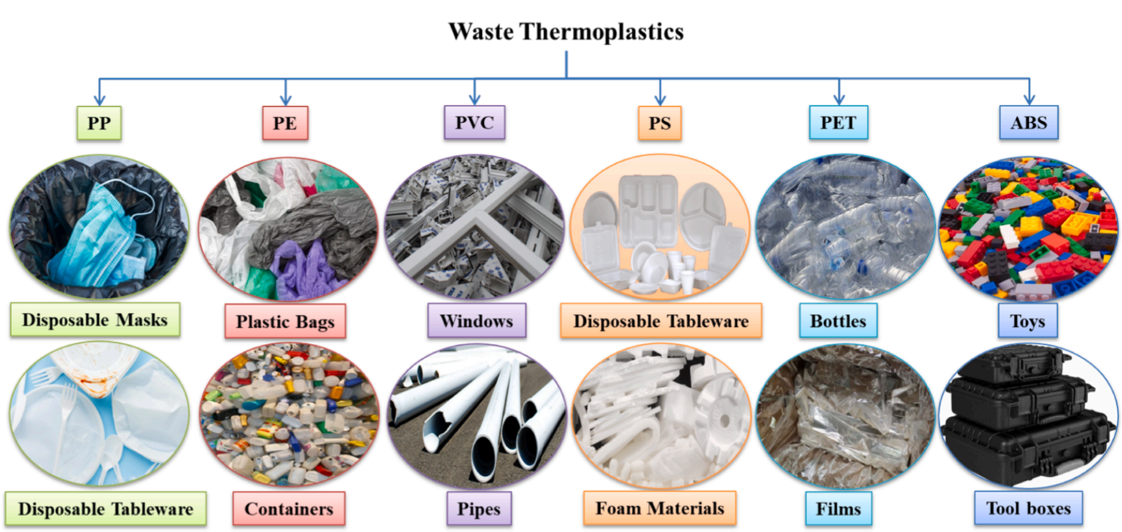

Fig. 1. Typical representatives of thermoplastic wastes.

Table 1
Major characteristics and challenges with waste plastics use in asphalt binder and mixture.

Plastic category	Type	Main products and properties	Challenges
Thermoplastic	PE	◆ Juice bottles, detergent bottles, packaging bags, etc. ◆ Melting temperature (HDPE & LDPE) = 133℃ & 110℃ [19] ◆ Non– biodegradable	◆ Variability in performance of modified binders ● Modified PE needs a higher temperature for blending
	PP	◆ Disposable tableware, masks, bottle caps, face shields, straws, etc. ◆ Melting temperature = 177.9℃ [20] ◆ Non-biodegradable	◆ High blending and paving temperatures required ● Variability in performance of modified binders
	PVC	◆ Pipes, raincoats, wire jackets, etc. ◆ Melting temperature = 152℃ [21] ◆ Chloride-based emission ◆ Non– biodegradable	◆ Chloride-based emissions could be released while blending at high temperature
	PS	◆ Disposable plates, bowls, cups, trays, etc. ◆ Melting temperature = 207 ~ 297℃ [22] ◆ Non-biodegradable	◆ Very high blending and paving temperatures required ● Variability in performance of modified asphalt binders
	ABS	◆ Toys, electronic devices, boxes, pipes, sheets, etc. ◆ No defined melting temperature, around 190 °C [23] ◆ Non-biodegradable	◆ Very high blending and paving temperatures required ● Variability in performance of modified asphalt binders
	PET	◆ Beverage bottles, mineral water bottles, films, etc. ◆ Melting temperature = 280℃ [24]	◆ Interaction limited to physical mixing ● Acts as filler for binder modification or as an alternative to fine aggregates in mixes
	PC	◆ Car dashboards, lampshades, helmets, discs, etc. ◆ Melting temperature = 232℃ [25] ◆ Non-biodegradable	
Thermoset	PU	◆ Foam boards, thermal insulation materials for buildings and so on, etc. ◆ Non-biodegradable	◆ Interaction limited to physical mixing ● Difficult to assure homogeneity in asphalt binder
	ER	◆ ER composites and fiber reinforced ER composites, floors, etc. ◆ Non-biodegradable	

as various thermoplastics have different blending temperatures. Specifically, plastics such as Polyvinyl Chloride (PVC) needs special attention due to the possible harmful emissions upon heating to elevated temperature. Other thermosets often require crushing and grinding process to convert them into powder form to be used as a modifier for asphalt mixtures.

2.2. Potential solutions

To manage the ever-increasing quantity of waste plastics, various recycling solutions have been proposed, including those that have been applied in the pavement engineering field with varying degrees of success [26–28]. When considering the different types of waste plastics, their recycling methods will be different due to their unique material attributes, melting temperature, and other relevant factors. The potential solutions when considering the use of these waste plastics in asphalt pavement-related applications are introduced below.

2.2.1. Waste thermoplastics

The most common recycling method adopted for thermoplastics is the mechanical-physical approach, which involves crushing and grinding them into small particles, followed by adding them to the asphalt binders and mixtures [6]. This process inevitably requires a very high temperature and a relatively long time for blending plastics with binders to ensure homogeneity in the modified binder. For instance, Kakar et al. [29] utilized a high-shear mixer to grind PET into 5 mm-10 mm PE pellets and then mixed them with hot binders for 60 min. at 170℃. Similarly, Diab et al. [30] tried using thermoplastics, including PP, HDPE, and ABS, to modify the virgin binder at 175℃ for 2 hrs. Likewise, Mohamed et al. [31] ground waste PS into 2 mm-4 mm granules and subsequently added them to a heated binder at 200℃ for several hours. These studies indicate that higher blending temperatures and longer mixing times are crucial for the efficient utilization of waste plastics in asphalt mixtures.

As far as repurposing waste PVC is concerned, only limited studies have been reported for its use in asphalt mixtures. For example, Köfteci et al. [32] collected various PVC powders from different sources and added them to the asphalt binder at 160 ~ 165℃ for around 15 min, followed by further blending at 180℃ for 60 min. Similarly, Ziari et al. [33] mixed waste PVC granules having size less than 3 mm into asphalt binders at 165℃ for 60 min. Although the rheological characterization was conducted in these studies, they did not mention the potentially large amounts of chloride-based emissions due to the chemical interaction between PVC and asphalt binder molecules under high-temperature blending conditions. To address this problem, Padhan et al. [34] tried a chemical recycling method to convert the waste PVC into additives using amine reagents and subsequently mixed it with virgin binder at around 165 °C for one hour.

In addition, waste plastics such as PET and PC have also been considered as a modifier to improve the performance of asphalt binders and corresponding mixtures. Different physical and chemical treatment approaches have been utilized for recycling these waste plastics, particularly for PET [35–37]. For physical treatment, the plastics are first crushed and pulverized into small particles, followed by adding them to asphalt binders and then to mixtures at elevated temperatures. For example, Abuaddous et al. [38] first shredded single-use PET water bottles, heated them to 250℃ and then ground them into powder using a ball mill before using them as an asphalt binder modifier. On the other hand, Moghaddam et al. [17] and Hassani et al. [39] used crushed plastic bottles to partially replace the aggregate in asphalt mixture and were found to be helpful in improving the mechanical performance of asphalt mixture. Based on these results, it is clear that high processing temperature and mixing methods are crucial.

To address the above issues of homogeneity and mixture stability with physical recycling, chemical recycling or chemolysis methods have been proposed by researchers, as they offer the possibility to convert PET into easily dissolvable additives based on solvolytic chain cleavage reactions. Chemolysis processes of PET include: glycolysis, hydrolysis, methanolysis, and aminolysis processes. Fig. 2 shows the basic chemistry involved in the different chemolysis processes. Several efforts have been made by researchers to degrade PET into additives using chemolysis methods and use as value-added modifiers for asphalt binders. For example, Abdel et al.[40] used glycolysis-based methods to convert PET into an “ecofriendly” modifier for asphalt binders. Similarly, Leng et al. [37] and Xu et al. [2] adopted the aminolysis process to degrade PET before further utilizing it as an asphalt binder modifier. Significant

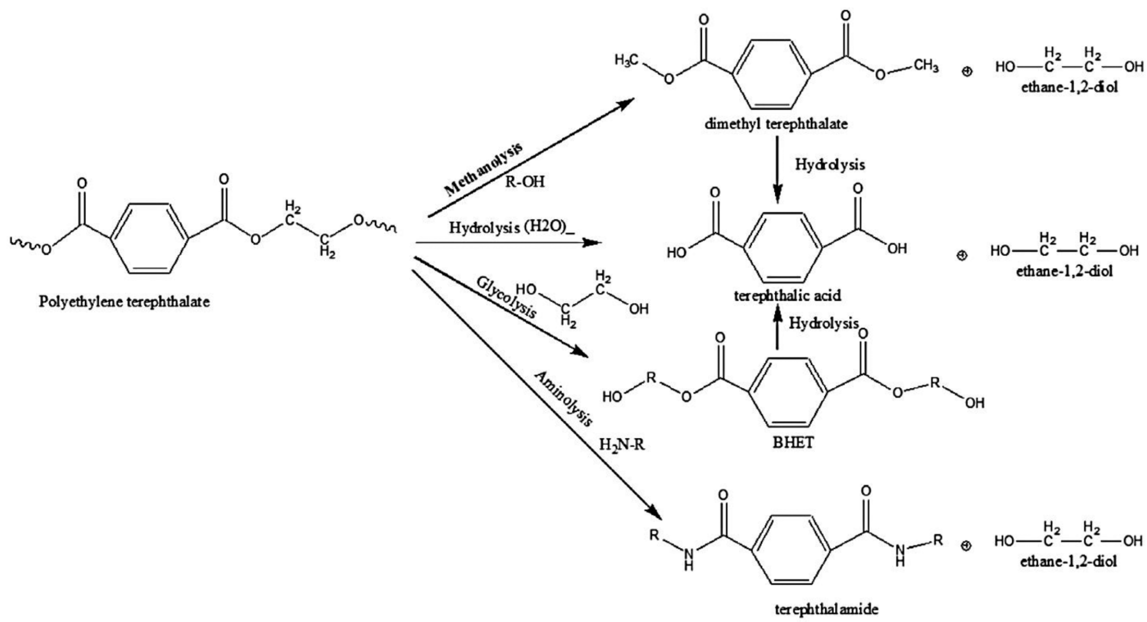

Fig. 2. Chemistry of different chemolysis processes [41].

improvement in mechanical performance parameters of asphalt binder and the corresponding mixture was reported in these studies. Overall, the use of different types of chemolysis-based treatments can be considered to be one of the potential approaches to repurposing waste plastics into asphalt mixtures.

2.2.2. *Waste thermosets*

Due to its crosslinking structural characteristics, melting processes and chemical treatments may not be suitable for recycling waste thermosets. Based on the current state of information available in this regard, these wastes are generally recycled into fine powders mechanically (e.g., crushing and grinding) to repurpose them in asphalt mixtures. For instance, Costa et al. [42] collected crosslinked waste Polyethylene (PEX) from waste pipes and cables, grounded them into 0.5–4.0 mm granules, and subsequently utilized them as a modifier for asphalt mixture. Similarly, Nameghi et al. [43] collected the recycled PEX wastes, ground them into 1.18–2.36 mm granules and then used them as a partial replacement for aggregates in asphalt mixtures.

Overall, it is clear that the most common recycling solution of waste thermosets for application in asphalt mixtures is to mechanically process them into fine powders. Although this solution may help increase the recycling outlets for waste thermosets, it is still essential to seek other methods to improve the long-term performance of modified asphalt mixture from multiple perspectives.

3. Rheological performance of asphalt binders and mixes containing waste plastic

Based on the nature of waste plastic, different degrees of changes to various mechanical performance parameters of asphalt binder and mixes can be expected. Therefore, it is paramount to understand different attributes of the rheological performance and the

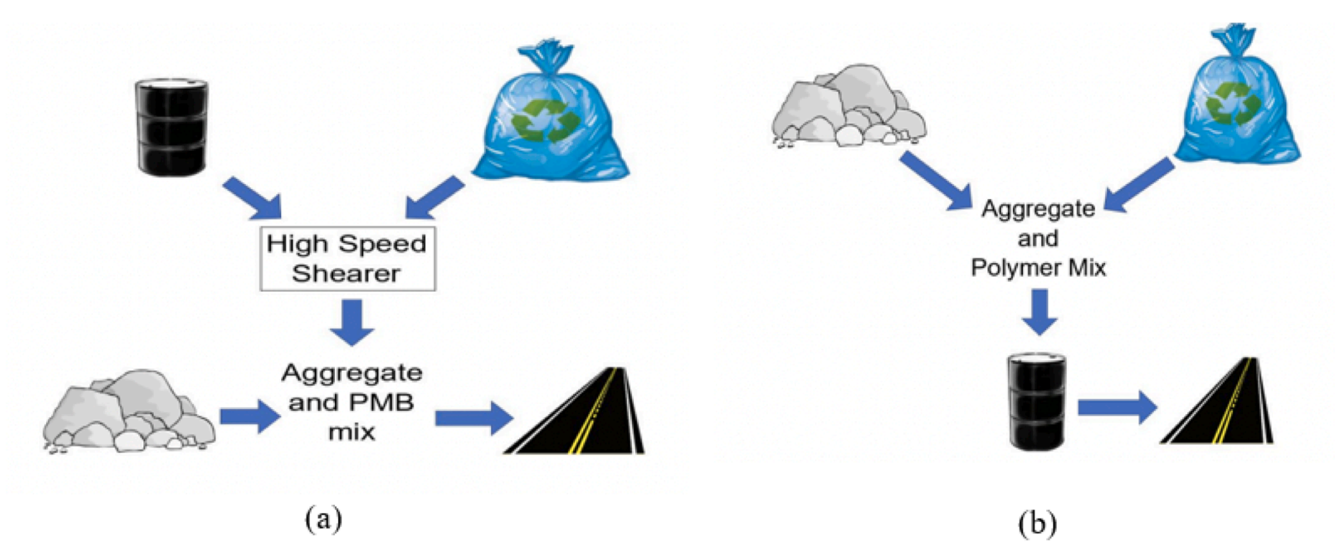

Fig. 3. Illustration of (a) wet, and (b) dry mixing process.

physicochemical interaction between various constituting components [44]. This section presents a succinct overview of the various prior literature regarding the performance evaluation of asphalt binder and mixes containing waste plastic. Firstly, a graphical illustration of two different methods to incorporate waste plastic in asphalt binder/mixes are presented in Fig. 3.

3.1. Wet mixing process

In a general sense, it can be assumed that when plastic is mixed with hot asphalt binder, it completely melts and forms a uniform system of constituents. However, this is an over-simplification of the physicochemical interaction as the real process would be more complicated. In reality, full solubility of plastics in asphalt binder is questionable, and its presence could lead to a separate phase in the blend during long-term storage and field use. For example, the difference in viscosities could lead to the situation wherein the polymer will not be dispersed in the binder to a significant extent, a requirement for a homogenous and compatible binder [45]. During the mixing process, the constituents of lower molecular weight in the asphalt binders will contribute to the swelling of the polymeric phase. Therefore, the viscosity ratio difference would be smaller than that of the waste plastic and unmodified binder. As a result, excessive polymer swelling would result in smaller interfacial tension and favour droplet breakup. An example of this is shown in Fig. 4a, wherein potentially excessive swelling when a certain type of LDPE was added to the asphalt binder can be observed, which was subsequently mitigated with the use of reactive chemical additives (Fig. 4b) [46]. Reactive additives, such as anhydrides, isocyanates, and epoxides, contain active groups that can react with specific functional groups. An illustration of such a reactive polymer that has been commonly used is Trans-Polyoctenamer (TPOR), which has previously been utilized to enhance the performance characteristics of different kinds of bituminous binders [47–48]. TPOR, with its distinctive chemical structure containing double bonds, has also been combined with cross-linking agents like sulfur, now widely available in pellet form. This combination has demonstrated the ability to further improve the elastic and rheological properties of the binders in some studies [46,49–50].

When looking at available literature, one study reported the formation of smaller drops during the mixing of Linear Low-Density Polyethylene (LLDPE) as compared to HDPE and LDPE due to decreased melt elasticity of the LLDPE in comparison to LDPE and HDPE [51]. Furthermore, another study reported that high molecular weight LDPE resulted in drop sizes that were larger than its lower molecular weight counterparts. Such results imply that a method to improve the properties of waste plastics in binders would be to reduce the melt elasticity. Another suggestion includes increasing the elongation flow component of mixing using rotor–stator mixers as opposed to a conventional stirred tank [52]. Coalescence is another major factor that prevents the larger inclusion of plastics into binders, as large inclusions will form if coalescence occurs. For example, many different plastic mixes have been shown to phase separate with asphalt binder without sufficient agitation. In that regard, a reduced particle size would result in diminished final particle size post melting. In a previous study, the use of LDPE, PP and HDPE as fillers were compared for binders after mixing and cooling. It was observed that LDPE had the most superior performance because the dispersed phase particle size of the LDPE was considerably smaller [53]. One study also investigated the development of different types of PE particles in binders at very high temperatures through isothermal annealing, even above their melting point. It was observed that each particle grew substantially with large swelling, with LLDPE showing the lowest swelling percentage [54]. This is illustrated in Fig. 5 and shows the generally low phase separation of LLDPE in the asphalt binder. Apart from this, another study reported that LDPE had more coalescence than HDPE in binders and recommended the use of reactive polymers to increase stability [55]. With the coalescence issue in mind, researchers have also adopted chemolysis methods such as aminolysis to convert waste PET into easily dispersible additives, which also helps in improving overall binder performance [35,37].

3.1.1. Mechanical properties

In general, the addition of plastics generally increases the stiffness of binders and properties directly related to it. The effects of these plastics on rutting, fatigue and strength characteristics are discussed below.

Effect on rutting performance: When considering the reported results related to rutting, G*/Sinδ is a commonly used parameter for examining the rutting performance at the binder scale. This parameter has been shown to correlate well with rutting performance, and higher value of this parameter is generally desired. Studies have shown that adding HDPE increased this parameter compared to the base asphalt binder [56]. Likewise, other works with LDPE, HDPE and PET have

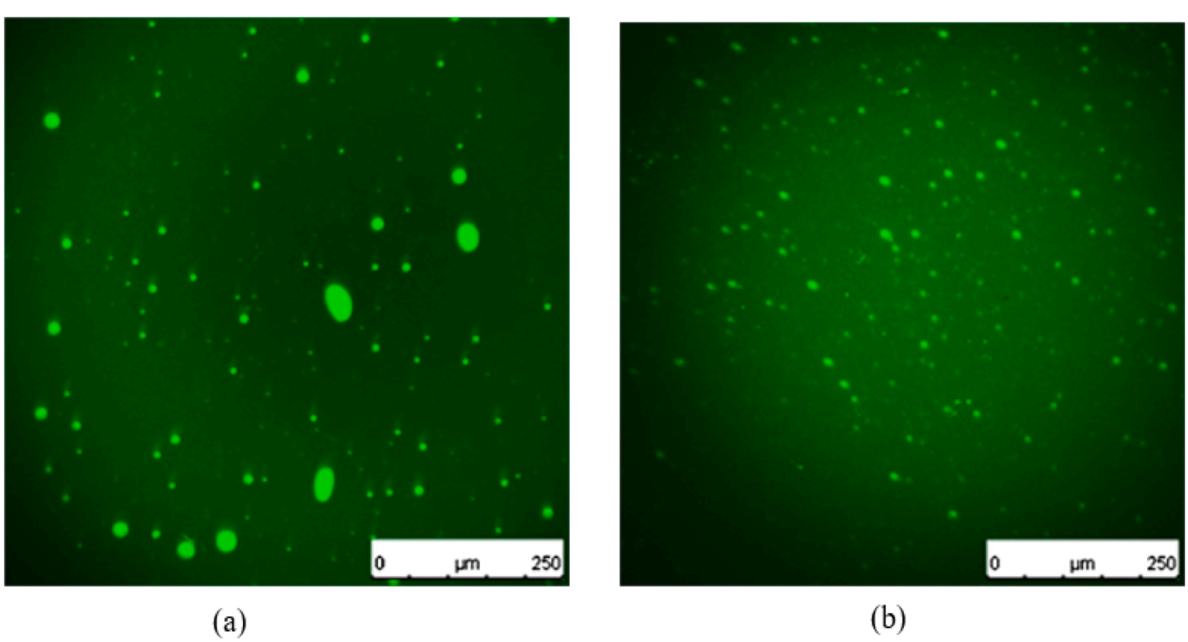

Fig. 4. Microscopic image for (a) excessive swelled, and (b) uniformly distributed LDPE in asphalt binder [46].

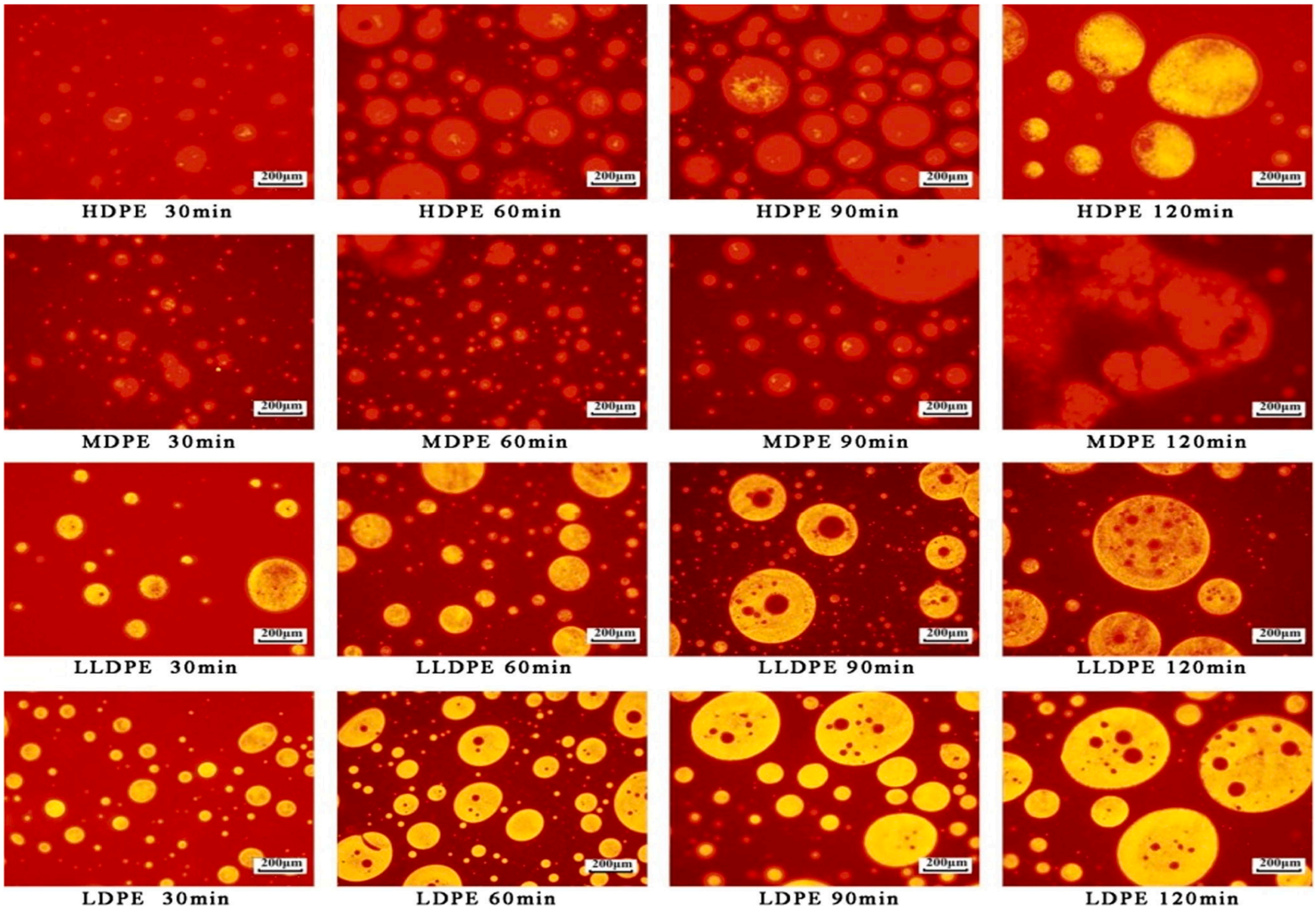

Fig. 5. Morphology evolution of PE binders under annealing [54].

reported similar results [46,57–59]. Apart from these works, other studies have also used other additives, such as waste crumb rubber, in synergy with plastics and have also shown improvement in the rutting performance [60]. In addition, studies have also utilized the non-recoverable creep compliance (J_{nr}) parameter from the Multiple Stress and Creep Recovery (MSCR) test [61]. Generally speaking, most of the reported studies have reported a reduction in the J_{nr} value with waste plastic addition, which alludes to an improvement in the rutting performance-related properties [62–63]. One study also utilized chemical pretreatment methods to convert PVC into amine-based additives and showed improvement in the rutting performance of asphalt binders [34]. At the mixture level, studies have been conducted using the Hamburg Wheel Tracking (HWT) test to investigate the rutting behaviour. One study reported improved rutting behaviour with the addition of 3% and 5% HDPE [64]. Additionally, the use of grafting functional groups such as maleic acid was also found to be helpful in significantly enhancing the rutting performance of LDPE-modified asphalt binder [65].

Effect on fatigue performance: The introduction of plastic components in asphalt mixtures can attenuate fatigue-related failures. For example, interfacial weakness in the composite binders could lead to the occurrence of temperature variations due to asymmetric thermal expansion, which may lead to the development of tensile stresses. It was reported that waste PE did not change the failure in terms of the number of cycles, whereas other modifiers such as Styrene-Butadiene-Styrene (SBS) and crumb rubber improved the fatigue life [66]. Other studies have, however, reported different results. One study indicated that the failure was reduced by a factor of about 5 and 3 when 7% and 6% of HDPE, respectively, were added to the asphalt binder [67]. Another study showed that the fatigue life was significantly improved with the incorporation to 2% and 5% by weight of HDPE to asphalt binder [30]. The fatigue life was also seen to be improved when chemically treated waste PET was utilized [68]. This study also insinuated the possibility of PET-based amine additives to chemically link with asphalt binder molecules and enhance performance.

Mixture strength: Generally speaking, the incorporation of reasonable percentages of plastics results in increased tensile strength of asphalt mixtures. One study showed that the use of small particle-sized HDPE resulted in a 15% increase in the Indirect Tensile Strength (ITS) value [64]. When comparing the use of different types of plastics on the same mixtures, it was reported that 4% HDPE produced 10% improvement in the ITS value compared to no improvement with the addition of 3% PP [69]. In another study, the addition of LDPE at 6% improved the ITS value by 15% [67].

Typically, it has been observed that the ITS values will rise up to a certain extent with the percentage increase of waste plastics and then start to decrease. Different studies have shown this trend with LDPE, where small additions improved the ITS values and larger additions produced strength which was even lower than the control mixture [18,70]. These results are consistent with the underlying logic that the larger the volume of plastics, the higher will be the degree of coalescence in the mixes. Therefore, the percentage of plastic at which this downturn occurs will vary greatly and depend on the interfacial properties between the components, mixing techniques adopted, etc.

3.2. Dry mixing process

In the dry mixing process, waste plastics are directly added to the asphalt mixture as either a replacement for aggregate or mixture modifier. The aggregate replacement approach is commonly advised for waste plastics with relatively higher melting points (e.g., PP, PC, PS, PET) (i.e., typically above the production temperature of asphalt mixture). Likewise, mixture modifier approach appears to be useful for most of the waste plastics (e.g., PP, PE, PET, PS and many more) except PVC due to concerns associated with the generation of chlorine-based dioxin fume [4]. The following section provides the summary of the mechanical properties of the asphalt mixture containing waste plastic incorporated using the dry method.

3.2.1. Mechanical properties

Similar to the case of wet mixing, the addition of plastics using dry process was found to be increasing the stiffness and its related properties of the asphalt mixtures. The effects of these plastics on rutting, fatigue and ITS characteristics are presented below.

Effect on rutting performance: Several studies have shown that there is a general improvement in rutting resistance related parameters such as ITS, Marshall stability etc. with the addition of different types of waste plastics such as PET and PVC [71,72]. Although different studies have reported improved rut resistance of asphalt mixture with the inclusion of PET; the corresponding effect was found to be dependent on PET size [73–74]. Similar to the case of wet mixing, the optimum percentage of improvement was seen at some arbitrary dosages, after which the addition of plastic seemed detrimental to the performance [75].

Effect on fatigue performance: Studies in this area indicate that the fatigue properties of asphalt binder or mixture containing plastics that do not melt during mixing are not as negative as for plastics that do melt during the processing. One study reported improved fatigue performance by ten folds with the addition of 10% PET to asphalt mixture [34]. Additionally, other studies have also reported generally constructive effects on fatigue performance by the addition of PET [17,76–77]. Besides PET, the addition of other plastics, such as polyamide fibres and PVC also reported positive effects on the fatigue performance of asphalt binder and mixtures [33,78].

Mixture strength: Studies have largely indicated that the addition of waste PET increases the tensile strength of asphalt mixtures. However, this seems to be the case when an optimum amount of PET is added, and any amount exceeding that was found to be detrimental to the performance [79]. For example, research on porous asphalt mixtures indicated that the addition of PET improved the ITS value of the asphalt mixture by three times [80]. Another study showed the largest increase in the ITS value for asphalt mixture containing smaller-sized PET as compared to their larger size counterparts [81]. In terms of other plastics, the addition of PVC at 5% and 10% was seen to increase the ITS value of asphalt mixture by 10% [33]. Another study for porous mixtures showed detrimental effects of PVC addition at its high loading rate [82]. Overall, various results seem to suggest that the particle size of waste plastic has a substantial influence on the strength of the asphalt mixtures.

3.3. Dry vs wet mixing method

Based on the results obtained from different studies, it seems that incorporating plastics in mixes using the dry method could be simpler when considering waste processing and logistical issues in the field. In addition, significantly more quantities of plastics can be utilized in asphalt mixtures using the dry method as it is added by weight (%) of aggregate as opposed to weight (%) of binder in the wet method. Nevertheless, one significant difficulty involved with the dry method is obtaining a consistent aggregate gradation. A way around this would be to incorporate additional pre-processing of plastics, which will also, unfortunately, have other supplementary costs involved. When looking at the types of plastic most suitable for each mixing method, the easiest and most practical way is to simply consider the melting temperature. Plastics with a low melting point, such as PE and PP, will be more suitable for the wet mix process as opposed to high melting point plastics, such as PET and ABS. Nonetheless, low melting point plastics have also been utilized using the dry mixing process, which essentially helps form a film on the aggregate surface, thereby improving the adhesive strength. Therefore, dry mixing (in comparison to wet mixing) can be considered more tolerant when considering plastics with both high and low melting points. However, the associated practical and technical issues need to be addressed. In the case of wet mixing, plastics having relatively lower viscosity would be more suitable than high viscosity plastics as it would ensure better dispersion in the asphalt binder. Melt Flow Index (MFI) is generally checked to evaluate the mixability of plastics and is a measure of the ease of flow of the melt of a thermoplastic polymer. Testing of MFI with different load weights also provides an indicative measure for the molecular weight distribution of the recycles waste plastic [4]. Several studies have shown the relation between MFI of polymeric additives and effective modification with asphalt binder [83–85]. When considering MFI metrics, higher MFI denotes plastics with lower viscosity, and lower MFI denotes plastics with higher viscosity.

4. Environmental and safety concerns

Although the use of waste plastic in asphalt mixtures could be a potential approach to address its disposal-related problems, it also raises several environmental and health-related concerns. Therefore, consideration of the hazardous emissions caused due to the heating of waste plastics during construction is paramount. Likewise, the release of plastic particulates and undesirable toxic chemicals during service life is another important aspect to deliberate on. Therefore, this section provides a critical assessment of potentially hazardous fume emissions during construction and the release of plastic particulate matter (including toxic chemicals) during the service life of waste plastic modified asphalt mixtures.

4.1. Fume emissions

Fumes generated during asphalt pavement construction have already been identified as a potential carcinogen by the International Agency for Research on Cancer in early 1987. The release of large quantities of hazardous Poly-Aromatic Hydrocarbons (PAHs) (e.g., naphthalene, acenaphthene, acenaphthylene, fluoranthene, fluorene, and chrysene, among few from a total of 16 high priority pollutants) and Volatile Organic Compounds (VOCs) (e.g., ethylbenzene, toluene, xylene, 4-ethyl toluene, 1,3,5-trimethyl-benzene) at high temperatures during the construction has been particularly identified as major concerns [86–90]. As far as asphalt fumes from asphalt mixture construction are concerned, the maximum permissible limit is set to 0.5 mg/m^3 over 8 h for long-term exposure and 5 mg/m^3 for 15 min short term exposure by environmental protection regulatory bodies like ACGIH and NIOSH [89,91]. Moreover, toxicological research shows that asphalt fumes can potentially induce gene mutations, which can cause long-term cellular damage [92–94]. Additionally, the generation of hazardous fumes (e.g., furans, dioxins, mercury, and polychlorinated biphenyls) has also been identified due to the burning of different kinds of plastics [95]. It is important to note that although there is sufficient research on the mechanical performance of asphalt mixtures with waste plastics, only recent studies in this area have raised the alarm regarding the potential increase in the generation of hazardous fumes during construction. In that regard, the combined effect of asphalt and plastics could create unfavorable conditions for road construction workers and the ambient environment.

Lindberg et al. [96] conducted a study to understand the impact of fumes generated from asphalt mixtures containing waste plastics (particularly waste PP and PE mixed in the 90:10 proportion) on human genotoxic effects. A positive correlation between damage to the human DNA (examined after every work shift) and PAHs from the fumes was identified. Similarly, Heikkila et al. [97] reported a significant change in the mutagenic activities with fumes generated from asphalt mixture with subsequent incorporation of waste plastic (PP:PS:PVC: polymethyl methacrylate as 79:11:7:3) to it. Such findings clearly provide potential evidence for health-related concerns arising from the utilization of waste plastics in asphalt mixtures. Likewise, Vaananen et al. [98] also reported that the concentration of aldehydes and resin acids (both are responsible for several types of body irritation) increased multiple folds with the incorporation of waste plastic (PE: PP as 90:10 (12% by the weight of binder)) in the asphalt mixture. As a result, the exposed workers complained of eye irritation, throat and skin infection. Similarly, Tsai et al. [99], and Conlon [100] raised concerns about the release of moderate to high level of toxic gases (e.g., acrolein, acetaldehyde, carbon monoxide, ethylbenzene, toluene, formic acid, formaldehyde, etc.) with the use of waste plastic in asphalt mixtures. Furthermore, Boom et al. [89] highlighted that along with the nature of waste plastic and its corresponding content, other extrinsic factors such as the temperature of the waste plastic modified mixture at the site, wind speed and direction, position and height of the particular person, the presence of sun and cloud coverage, the individual's behaviour such as smoking/non-smoking, food consumption, the onsite safety measures (from toxic fumes) etc. can significantly influence the final impact on an individual's health. Although these studies clearly highlighted the increase in the level of toxic gases with the addition of waste plastics to asphalt mixtures, other studies have provided counterarguments. For example, based on the findings from the fume-based measurement on asphalt mixture containing HDPE and PET, White et al. [101] argued that the fumes generated from such mixtures during construction will still be within the acceptable range. More recently, Boom et al. [89] argued that the toxic fumes emitted during road construction would be reduced with the addition of waste plastics due to the enhanced thermal stability of asphalt mixtures. Interestingly, this study further highlights that the findings related to the analysis of the concentration of a specific compound may be deceptive as a particular gas concentration may spike. However, the overall concentration of toxic gases (i.e., including all toxic gases) may still go down. Similarly, Boom et al. [90] also argued that one can expect a reduction in the emission of toxic gass when the melting point of waste plastics is higher than the construction temperature. Moreover, considering the influence of extrinsic factors (e.g., wind speed, cloud coverage) on individual health due to fumes generation, Boom et al. [89] particularly emphasized that laboratory-based fume emissions should not be used for developing occupational health and safety guidelines. This is because the limitations in field measurements such as wind speed, atmospheric conditions and reliability play an important role. Therefore, the need for developing proper validation methods to compare laboratory and field-based toxic fumes measurements was stressed.

4.2. *Leaching of waste plastic particulates and other toxic chemicals*

The release of microplastics (with sizes typically in the range of 50 μm −5 mm) into the environment has become a major concern in the recent past [102–103]. In addition, Chin and Damen [104] also identified the release of nanoplastics (particles with sizes in the range of 100–1000 nm) due to the breakdown of high crystalline plastics with its exposure to ageing, sunlight, rainfall and wear. Although the release of microplastics from asphalt mixtures containing waste plastic is not well understood so far, the corresponding environmental concern in the community is justifiable. This is because several researchers have reported that the presence of asphalt mixture constituents in different types of water bodies and the traces of micro and nanoplastics have been previously found in rivers [105–106], oceans [107–108]; sediments [109–110], and even in the open air [111]. These small-sized plastics can be easily ingested by fish [112], shellfish [113], and different types of other marine organisms [114], which potentially cause severe obstruction to their food track [115]. Moreover, it also releases toxic chemicals after degradation, which are harmful when consumed by humans [116–117].

In this direction, the interim report by NCAT et al. [4] on waste plastic utilization in asphalt mixtures categorically mentioned that leaching of toxic materials and contaminants such as Bisphenol A (BPA), Phthalates (both are particularly present in PET bottles and are proven to be responsible for the development and hormonal related issues in human and animals) [118–119], and microplastics are potential environmental concerns. Moreover, it also highlighted that the degree of toxicity and amount of microplastics generated using the dry mixing method may be potentially higher than the wet mixing method due to the use of higher waste plastic content in the dry mixing method. Subsequently, Enfrin et al. [120] performed a laboratory-based study on asphalt mixture (with binder content as 5.1% by the wt. of the mix.) containing different types of waste plastics (LDPE, PE, PP, PET, and ABS (1, 2, 4 and 6% by the wt. of binder for each type)) to understand the potential release of microplastics. The release of microplastics was clearly observed in this study, and the amount of microplastics from the wet mixing method was found to be significantly higher than the dry mixing method. In addition, the decrease in temperature and increase in acidity level of the environment was found to accelerate the microplastics release process. Such results clearly indicate that the contamination risk to the water bodies due to microplastics released from paved roads containing waste plastic in cold regions and regions susceptible to acid rains will be higher. Similarly, Guppy and Giustozzi [121] also attempted to examine the release of microplastics from asphalt mixtures containing waste plastic (recycled LDPE) in the laboratory. The analysis on the solid residues from collected water samples using Fourier Transform Infrared (FTIR) spectroscopy and microscopic analysis provided clear evidence for the presence of microplastics in the collected sample. Research in a similar direction was recently conducted by Abdalfattah et al. [122], in which the toxicity level of water leachate from asphalt mixtures containing waste plastic (HDPE and LDPE added through wet as well as dry process) was examined through zebrafish embryotoxicity test (to understand the biological interactions and corresponding responses within the investigated environment). No change in the heartbeat of the zebrafish was observed; in fact, the embryos responded with usual movements with touch-induced sensation. Therefore, unlike the earlier findings reported by Enfrin et al. [120], the observations from this study indicate that toxicity due to microplastics released from asphalt mixture containing waste plastic may not cause any potential threat to aquatic life, as well as to humans if consumed. Similarly, White [101] also reported that leached hazardous chemicals' toxicity level might remain within the acceptable range; therefore, it does not pose any threat to aquatic lives and human health.

In summary, the health hazard due to the release of PAHs and VOCs from asphalt mixture heating (or construction) has been clearly established. Likewise, the concerns associated with the presence of microplastics and different types of toxic chemicals in various water bodies are also well recognized. However, whether such a concern will increase or subside with further incorporation of waste plastic into the asphalt mixture is not clearly established so far. Moreover, the number of reported research works in this area (both on fumes and plastic particulates) are considerably low. Therefore, further research is required to fully understand potential environmental and health concerns and develop appropriate measures to minimize the corresponding effects, if any.

5. Life-cycle assessment and economic analysis

Life Cycle Assessment (LCA) is a commonly used method to quantify the environmental impact of a product through the end of its service life. It has been reported that energy consumption and Global Warming Potential (GHG) are the most commonly used attributes to characterize the impact of road construction materials [123]. Although the use of waste plastics in asphalt mixtures may deliver adequate engineering performance, it is critical for practical purposes to ascertain that its use is holistically feasible from other perspectives as well. Therefore, quantifiable metrics are required to ascertain if its implementation is both environmentally and economically feasible. When looking at CO_2 equivalent emissions, Pouranian and Shishehbor [124] reported that there would be a nearly 10% decrease when 8% virgin PP is replaced by waste PP of the same amount in asphalt mixtures. Similarly, using waste PP would decrease emissions by around 16% when it replaces traditionally used SBS modifiers [124]. One of the early studies in the LCA domain evaluated the use of PET, PU, glass and crumb rubber for various types of asphalt pavement construction [125]. It was reported that the use of such wastes led to the reduction of material costs, greenhouse gases and savings of non-renewable energy. Some studies also used a cradle-to-cradle LCA modeling approach and reported positive effects in terms of GHG emissions and energy use when mixtures containing high quantities of PP and rubber were considered [126]. LCA-based tools were also utilized to evaluate the effect of using various types of PS wastes in mixtures. It was reported that the inclusion of PS improved the resilience of pavements and provided comparative environmental impact [127]. Other than this, one study reported a reduction in energy consumption of around 2% when waste plastic-modified asphalt mixtures were used as surface course material instead of conventional materials in the asphalt mixture [128].

More recently, a multi-attribute Gray Relational Analysis (GRA) based approach was adopted by Santos et al. [129] to compare several replacement ratios of virgin materials by plastics. The results indicated that the use of plastics (both dry and wet methods) has the potential to be more environmentally friendly than traditional asphalt mixtures depending on the use case scenario. For example, it was reported that climate change, ozone layer depletion, acidification and photochemical oxidation impacts were reduced by 8.6–15.6%, 7.2–13.4%, 4.7–8.9% and 4.5–8.6%, respectively, when recycled plastic pellets were incorporated in place of traditional polymers using the wet method. Using the dry method, on the other hand, as an aggregate replacement was shown to also benefit the environment to a lower extent, and their use at small percentages (i.e., 2.5% or less) could increase the recycling rate of plastics without substantially harming the ecosystem. In general, it was stated that the type of plastics and mixing technology (i.e. wet or dry) to be used in the field will depend on the classification of the road (i.e. traffic levels) and proximity to the reprocessing facility. Another study replaced 25% asphalt binder with low-cost waste plastics composed of cables and household plastic wastes and studied its environmental impact, among other attributes [130]. Based on LCA analysis, it was reported that the use of plastics resulted in a 17% reduction in environmental impact. Likewise, Yao et al. [131] reported that the use of PET-modified asphalt can lower GHG emissions by around 25%. In addition, other studies have also reported a positive environmental impact when using different types of plastics in asphalt mixtures [132–133]. Overall, findings from the studies conducted so far appear promising regarding the potential environmental benefits with the incorporation of waste plastics in asphalt mixtures. Nevertheless, further studies are still required to provide more quantitative data considering different factors such as logistics, different types of locally available plastics, and field-based pavement performance data. Moreover, many of these studies have used simplistic and potentially outdated models; therefore, a more robust analysis using the latest developments is desired.

From an economic perspective, using waste plastics in mixtures can reduce the need for virgin polymers; thereby, there is considerable potential for materials cost savings. Additionally, along with improved pavement performance, the reduced need for landfills may have supplementary economic benefits. In this direction, Vasudevan et al. [134] reported that replacing 10% of virgin bitumen with waste plastics for a 1 km road of 3.75 m length can save the financial equivalent of about 1 ton of bitumen. Similarly, Vila-Cortavitarte et al. [127] added three different types of plastics such as high impact PS, crystal PS and conventional PS (from hangers) to asphalt mixtures (using the dry method). It was reported that the increased life cycle provided by the presence of PS might bring a certain degree of financial benefits. Additionally, it was reported that the dry method of mixing might be more economically viable, as there is no additional mixing step for modification of binder or further chemical recycling. Likewise, Yao et al. [131] reported that using 2% PET (by weight of virgin binder) has the potential to reduce the overall cost by 14.5–26.2% during a 50-year analysis period. However, it is important to note that many of these studies have used simplistic financial assumptions that may not reflect the entire economic analysis involved in the whole lifecycle process. In that regard, White and Reid. [135] suggested investigating the additional hidden costs associated with the processing, recycling, and transportation phases during the incorporation of waste plastics into asphalt mixtures. Khoo [136] reported that the plastic recycling process would be economically efficient only when specific types of waste plastic streams are available in sufficient volume. However, this may be difficult in a real-life scenario as the composition and properties of waste plastics could differ from region to region. Therefore, at this stage of technological maturity, with a good understanding on many direct and indirect factors, the use of plastics in asphalt pavement would need extra support and encouragement from transportation agencies and environmental policymakers. Lastly, it has been reported that using Life Cycle Cost Analysis (LCCA) to examine the quantitative economic impacts of incorporating waste plastics into roads is still a challenge due to the lack of data on the service life of plastic roads [5]. Hence, further analysis using the cradle-to-cradle approach is required in various aspects of this realm, such as in terms of plastic collection, treatment, application, performance, and recycling.

6. Field projects related to the use of waste plastic in asphalt mixtures

Although several research works are available on the laboratory-based performance of asphalt binders and mixtures containing different types of waste plastics, the corresponding studies related to field validation are limited. Nevertheless, considering the ever-growing need for sustainable construction practices, several field-based pilot studies have been conducted across the globe in the recent past. Such studies will not only help researchers validate the laboratory-based findings but also help in identifying associated practical challenges in the field and develop guidelines for maximizing its utilization in the roadway infrastructure. The following section presents a high-level summary of field-based studies related to asphalt mixtures containing waste plastic across the world to promote sustainable construction practices.

6.1. India based field projects

As per the recent report by Economic times [137], India's annual production of waste plastics is about 3.5 million tons, which has almost doubled in the last five years. Moreover, TERI [138] indicates that plastic waste generation in India was about 11 kg/capita/year in 2013–2014, which is expected to increase to 20 kg/capita/year by 2022. This report also indicates that about 40% of the total plastic waste in India remains mismanaged. Regarding some of the initial field performance based pilot projects (containing waste plastic in asphalt layer), detailed structural and functional field evaluation was conducted on seven different stretches from 2002 to 2007 in different parts of Tamil Nadu (situated in the southern part of India). Dry mixing method was utilized in all the cases to mix different type of waste plastics (PE, PP, PS) with recommended dose of 10% by the weight of asphalt binder. Virgin asphalt binder having penetration grade 60/70 was chosen in every case. Although mix design related information is not available, detailed forensic investigation was carried out after between 2 and 6 years after the construction for different stretches. As a part of this task, different structural (strength, density, rutting, cracking, potholes), and functional (roughness, skid resistance, etc.) evaluation was carried out. None of the stretches showed any sign of potholes, rutting or ravelling even after 2–6 years of construction. In the last few years, Chennai alone utilized about 1600 tons of waste plastic in constructing about 1035 km of road. Subsequently, based on the encouraging outcomes from such pilot projects, similar construction started in other geographical regions of the country [139]. For example, different stretches were constructed in Ahmedabad in 2019 and have so far survived three monsoon seasons without any visual defects. Likewise, a similar pilot project was laid in Shimla in 2019 and found to be performing well without any visual defects after three winter cycles containing heavy snow (with design traffic close to 10 million standard axles). Similar success was observed for such projects in other parts of the nation. It is to be noted that the above pilot projects have utilized dry mixing process for the utilizing mixture of specific type of waste plastics (LDPE, HDPE, and PET). Virgin asphalt binder with penetration grade 60/70 or 80/100 was utilized in these pilot projects. Waste plastic content was kept between 6% and 8% by the weight of asphalt binder (depending on the rainfall of the area) for dense graded asphalt mixtures as well as open graded asphalt mixtures. In fact, the government of India also suggests utilizing waste plastic for rural and national highways as a default mode of periodic maintenance for roads falling within 50 km of peripheral areas with a population of more than 5 million [140–141]. Overall, more than 33700 km of asphalt pavements (including above 700 km of national highways) till date in India have been constructed using waste plastics.

6.2. United kingdom (UK) based field projects

About 1.53 million tonnes of waste plastic were generated in 2016 alone, indicating an increasing trend of about 24% since 2010 [142]. Although the authors of this research article didn't find any UK-based large-scale field studies, several small-scale roads have been constructed in the recent past using waste plastics in several parts of the country. The typical waste plastic content (mixture of a wide range of thermoplastics in daily use) considered for such projects was found to be 6% by the weight of the virgin asphalt binder. Construction agencies have primarily adopted the wet method for adding different types of thermoplastic wastes which are destined for landfill or incineration. For example, pavement resurfacing work (stone matrix asphalt as the asphalt mixture type) at three different locations in London with waste plastic content equal to 6% by the weight of virgin asphalt binder at different sections was completed in 2018. In addition, commercial plastic was also utilized for a separate stretch for comparative analysis. About 600 kg of waste plastic was utilized in this project, which was found to be helpful in saving about 1416 kg of CO_2 emission. Detailed forensic investigation on field cores taken after a year (using indirect tensile stiffness test, fatigue life test, and wheel track rutting test) showed equivalent or better performance for sections containing waste plastic than commercial polymer. Similarly, about 414 kg, 1800 kg, 2300 kg, 150,000 single-use, 264 kg, 500 kg, 1,100,000 single-use, and 1000 kg waste plastic (thermoplastic type) were utilized for asphalt pavement resurfacing work (stone matrix asphalt was again adopted as the asphalt mixture type) in Dalmarnock, Denbighshire, Dumfries & Galloway, Bristol, Cumbria, Coventry, London, and Dumfries, respectively. Similar to the earlier case, waste plastic quantity equal to 6% by the weight of virgin asphalt binder was considered for these pilot projects. As a result, an equivalent amount of about 10224 kg CO_2 emission was saved through these projects [143]. A representative photo of a trial section in Coventry city council is provided in Fig. 6. Along with reducing CO_2 emission, such field projects were found to have positive structural performance thus far and are expected to perform well in the years to come. Moreover, considering such promising performance, the transport department announced an investment worth £23 million for pilot projects across nine different locations in the country for similar projects, though the information on the type and quantity of waste plastic, asphalt mixture type, etc. is not available in the public domain [144].

6.3. United States of America (USA) based field projects

The review of the literature showed that about 35 million tons of waste plastic were generated in the USA in 2018 alone. As per the Environmental Protection Agency [145], polypropylene plastic waste accounted for about 32% of the total plastic waste, followed by polyethene, which accounted for about 29%. Yin [146] reported that about nineteen field sections with asphalt layer containing waste plastic had been laid in different parts of the USA since 2018 using dry as well as wet methods. For example, a 137 m long local road was constructed in Wisconsin in 2021, in which about 450 kg of waste LDPE (0.5% by the weight of aggregate using the dry method) was utilized. Similarly, a parking lot at Cincinnati Technology Centre (CTC), Ohio constructed a 2414 m^2 parking area in 2020 in which about 1945 kg of waste LDPE (0.5% by the weight of aggregate using the dry method) was utilized. Likewise, about 1594 kg of LDPE-based waste plastic (using the wet method) was utilized to construct two private roads in Texas in 2019–2020. Further, to examine the most appropriate way of adding waste plastic to the mixtures, NCAT constructed two test tracks (constituting app. 10 million ESALs over the period of two years) (610 m long each for wet and dry method) in 2021 and their short-and long-term performance is currently under investigation. Waste plastic (LDPE/LLDPE type) content was kept at 1% by the weight of asphaltic mixture for the wet method, whereas 0.5% by the weight of aggregate for the dry method. In addition, a 3.2 km long local road is proposed (using wet as well as dry method) at the University of Missouri campus and is expected

Fig. 6. Trial section with asphalt mixture containing waste plastic in Coventry City Council, UK [143].

to utilize about 10 tons of recycled waste plastic (LLDPE type waste plastic). Two different types of asphalt mixtures (one mix having 0.5% recycled LLDPE and 0.9% reactive ethylene terpolymer by the weight of the mix while other mix having only 0.5% recycled LLDPE by the weight of the mix) were adopted for this pilot project [4]. Similarly, the public work office in Los Angeles made an announcement in 2020 to construct major city roads using asphalt mixtures containing waste plastic (recycled PET based used water bottles) and evaluate their structural performance under heavy loading (expected to utilize about 150,000 plastic bottles per lane-km) [147]. It should be noted that the information on the quantity of waste plastic, asphalt mixture type, etc. is not available for this pilot project in the public domain.

6.4. Australia and New Zealand based field projects

Australia generated almost 2.5 million tons of plastic waste in 2018–2019, which was marginally lower than the corresponding waste generation in 2016–2017 (≈ 2.6 million tons). About 32% of total plastic waste in Australia is HDPE. Among various sources, households contribute about 47% of the total plastic waste. Moreover, as per dept. of agriculture, water and the environment, the export of mixed plastic waste has been banned since July 2021 [148]. Australian Road Research Board (ARRB) and research universities in Australia have put extensive research efforts in the last couple of years into exploring the feasibility of waste plastics utilization in asphalt mixtures [149–152]. As far as the method for adding waste plastic in Australia is concerned, AP-T365 [153] highlights that the wet method is suggested only in cases when the melting point of waste plastic is below 160°C in order to produce homogeneous plastic modified asphalt binder. On the other hand, dry method is suggested for waste plastic having melting point above 200°C to retain bulk density, shape and softening. Along with structural performance, a strong emphasis has also been given to fume emission during construction, the release of microplastics, and recyclability potential. As far as field projects are concerned, the first trial stretch was laid by the Brisbane city council in 2018. Although no information is available regarding the field performance of this project (4.5%- 6% by the weight of asphalt binder was utilized with different grades of virgin asphalt binder), comparing its performance with the asphalt mixture containing conventional elastomeric polymer modified binder was one of its prime objectives [149]. Likewise, a trial stretch was laid in Victoria in 2018, in which, along with other waste materials (e.g., glass bottles, printer cartridges), about 200,000 single-use waste plastic was utilized (5.6% by the weight of asphalt binder) [154]. Based on the detailed investigations (stiffness modulus, wheel track test, fatigue life test, moisture sensitivity test, etc.), it is expected that the trial stretch will last about 65% longer than conventional asphalt pavement. Another project in Victoria recently utilized about 746,000 plastic bags and additional waste materials (RAP and printer cartridges) and has been performing significantly better than conventional asphalt pavement [155]. The New South Wales government also utilized about 176,000 single used plastic bags and additional wastes (glass bottles and RAP) in constructing asphalt pavement in 2018 and has been reported to be performing well so far [156]. Similar to the Australian experience, an asphalt pavement stretch containing waste plastic (3100 single used plastics) was laid in the recent past in the Christchurch Airport area, New Zealand, to accommodate extremely heavy traffic loads. Likewise, one of the city council roads in New Plymouth, New Zealand, utilized about 83,300 plastic yoghurt pots in laying the asphalt road.

6.5. Pakistan based field projects

As per Andersen [157], Pakistan generated about 3.9 million tons of plastic waste in 2020, which is expected to increase to about 6.12 million tons per annum by 2050. The first-ever 250 m long asphalt pavement containing waste plastic in Pakistan was recently constructed in 2021 under the “world without plastic” scheme. About 8 tons of waste plastics, particularly recycled PET bottles and cups, were utilized in this pilot project, and reports indicate good performance of these roads so far [158]. Upon the satisfactory performance of the two ongoing pilot projects, the government is expected to implement this technology on a larger scale in the other parts of the country [158] (Fig. 7).

6.6. China based field projects

According to one of the estimates, China is the largest waste plastic generator, contributing to one-fifth of total waste plastic globally. Moreover, the annual production of waste plastic per person in China is about 18 kg/year. From food packaging to different kinds of single-use plastics, about 130 million tons of plastic were generated in 2019 alone [159]. Therefore, China has banned importing 24 different kinds of waste, including plastics, since January 2018 [160]. Also, the government is encouraging the recycling of waste plastic in the country, including exploring its potential application in infrastructural development projects. In this direction, the first-ever pilot project-based 300 m asphalt pavement containing waste plastics was recently built in Shanghai. More than 6000 discarded polyethylene-based recycled milk bottles were utilized in this project using the wet method of mixing. The company associated with this project is committed to utilizing around 1 million tons of waste plastic by 2030 [161].

6.7. South Africa (SA) based field projects

Per capita plastic waste generation in SA is 41 kg/year, which is significantly higher than the global average of 29 kg/year. Approximately 40% of the generated waste plastic in the nation is mismanaged. Moreover, around 79,000 tons of waste plastic leak into the ocean every year, which is a significant threat to aquatic life [162]. The first-ever 80 m long asphalt pavement containing waste plastic (6% by the weight of virgin asphalt binder using wet mixing method) was constructed in 2019 in the KwaZulu-Natal (KZN) province of SA. This pilot project utilized

Fig. 7. Trial section containing waste plastic in Islamabad, Pakistan [158].

Fig. 8. Paving project having asphalt mixture containing recycled waste plastic in KZN province of South Africa [164].

about 6770 PE-based milk bottles [163] (Fig. 8). Another trial section of around 400 m was laid in the same year on the outskirts of Durban, in which about 40,000 single-use two-litre milk bottles were utilized [164]. Moreover, South Africa National Roads Agency pledged to utilize about 200 tons of waste plastic in constructing the N3 highway connecting Johannesburg and Durban [165]. Likewise, a 270 m trial stretch was laid in Jeffreys Bay in 2019, in which about 145,000 tons of single-use waste plastics were utilized. In fact, along with improved structural performance, it also reduced CO2 emission by an amount of about 285 kg [143].

6.8. Indonesia based field projects

As per the World bank [166], Indonesia produces about 7.8 million tons of plastic annually, and more than half of that waste remains mismanaged. A major part of mismanaged waste plastic goes into the sea, which is highly hazardous for ocean habitats. In fact, Indonesia is the second-largest country responsible for marine waste plastic. Therefore, along with several policies on waste management, the government of Indonesia is encouraging to use waste plastics for sustainable development [167]. An asphalt pavement with a total length of 700 m (600 m using recycled LDPE in the asphalt mixture and another 100 m without waste plastic for comparison purposes) was laid at the University of Udayana, Bali, in 2017 (Fig. 9). 6% by weight of virgin asphalt binder (with penetration grade 60/70) was utilized using the dry method for this project after detailed laboratory investigation using Marshall mix design followed by mechanical performance-based evaluation such as resilient modulus, wheel track rutting, and beam fatigue test. The waste plastic was initially added with heated aggregate for proper coating over its surface and then mixed with hot asphalt. A detailed forensic investigation was also carried out on samples collected from the field. The stretch containing waste plastic was found to be performing better than control asphalt pavement (i.e., without waste plastic) [168]. The success of this pilot project has prompted several other parts of Indonesia (Bekasi, Makassar, Surakarta, Surabaya, Tangerang, and Depok) to construct asphalt pavements using waste plastic during 2017–2018 [167].

In addition to the field studies presented above, several other countries, such as Canada, Scotland, France, Italy, Thailand, etc., have also laid out similar pilot projects to utilize different kinds of waste plastic in the recent past. Likewise, other countries such as Singapore and Cambodia are also expected to start similar projects in the near future.

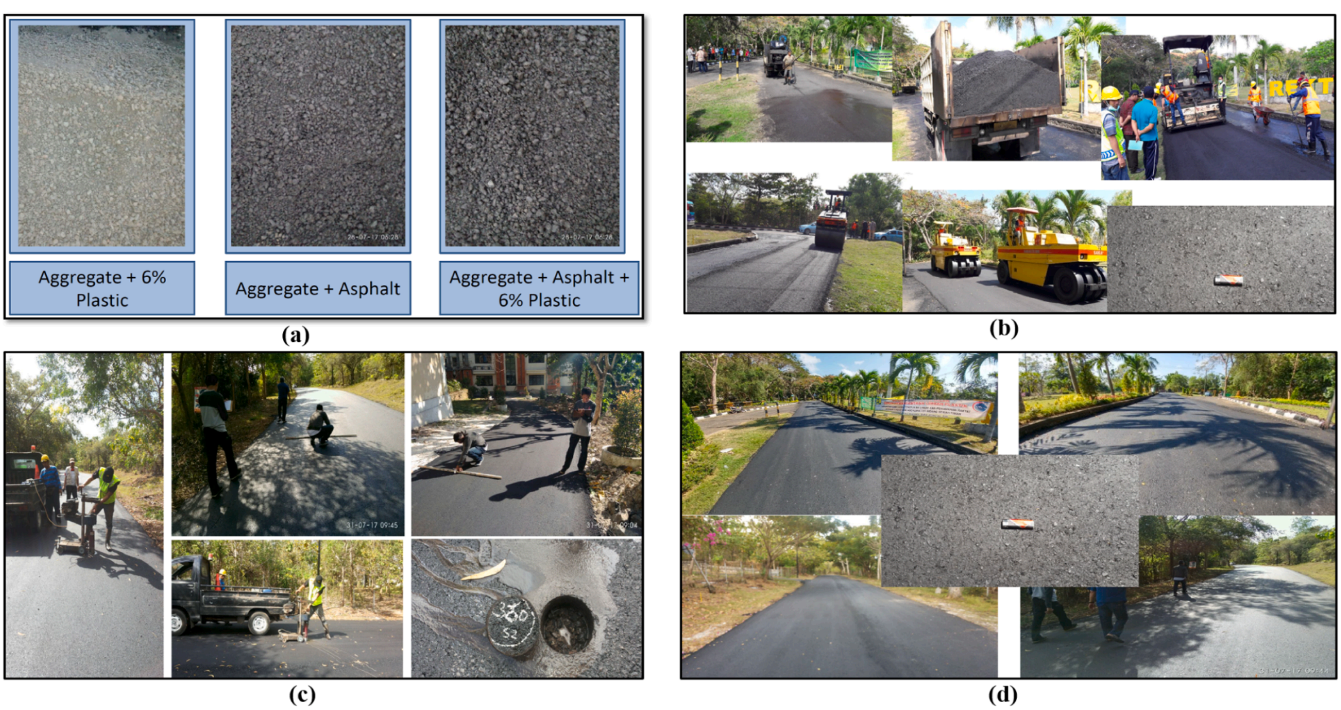

Fig. 9. (a) Trial mixes, (b) spreading and compaction, (c) quality control, and (d) finally paved surfaces for test section containing waste plastic at the University of Udayana, Bali [169].

6.9. Typical challenges for field use

Although the use of waste plastic has been implemented in several countries, as discussed above, a few different challenges and limitations have also been identified. For example, the need for continuous agitation or an additional compatibilization agent (to avoid phase separation-related problems) has been identified as one of the challenges with the wet mixing method. As a result, the overall construction cost using the wet method was reported to be relatively higher than the dry method. Similarly, due to significantly lower interaction time between waste plastic and different components of asphalt mixture in the dry method, some plastic melts and becomes part of the asphalt binder while others may coat the aggregate and also remain solid as a part of the aggregate matrix. Consequently, inconsistent performance is one of the major concerns reported with the dry method. Likewise, the installation of additional units/modification to the conventional batch mix plant for waste plastic addition using dry methods is another issue highlighted by some of the construction agencies. Moreover, challenges in the use of waste plastic using cold feed conveyors (in the dry method) have been reported in some cases. Such practice is not advisable as the temperature in the dryer drum can reach as high as 760℃, which is significantly higher than the flash point for virtually all types of waste plastics. Lastly, collecting and sorting targeted waste plastics suitable for paving applications is also identified as one of the challenges.

7. Conclusion

This review article illustrates the comprehensive background and relevant information on the different pertinent aspects associated with the use of waste plastics in asphalt mixtures. Firstly, the challenges associated with waste plastic utilization in asphalt mixtures, including the influence of different types of waste plastics on the mechanical performance of asphalt binder and corresponding mixtures, are discussed. Following this, the associated environmental concerns and life cycle cost-related aspects are also deliberated. Lastly, an exhaustive review of existing field trials on waste plastic modified asphalt roads is provided. Based on the various discussion and analyses of current literature works, main findings and suggestions are summarized as follows:

- Although many types of waste plastics (including thermoplastics and thermosets) have shown potential to be used as modifiers for asphalt mixtures, some of its characteristics such as high melting temperature and poor high-temperature storage stability are some of the major concerns associated with its practical applications. As far as waste thermoplastics are concerned, the recycling method adopted is normally the mechanical-physical approach, which involves crushing and grinding waste plastics into small particles before addition to asphalt binders and mixtures. Other than that, the use of chemical treatments such as aminolysis has also been reported to be very helpful for its effective value-added utilization in asphalt mixtures in order to tackle high melting temperature and poor high-temperature storage stability related concerns. As far as waste thermosets are concerned, melting processes and chemical treatments are not directly suitable due to their crosslinking structure. Therefore, the most common recycling solution for waste thermoset plastics currently is to mechanically process them into fine powders and then utilize them as an asphalt binder modifier or filler. When comparing the two types of plastics, thermoplastics generally present the greatest scope and utility for asphalt pavement related modifications.
- When considering the mechanical performance of waste plastic modified asphalt binders and mixtures, such addition has been generally found to be helpful in improving its strength and durability-related properties. However, the degree of change in the corresponding parameters was found to be largely dependent upon the method used to incorporate the waste plastic into the asphalt mixtures (wet or dry method), waste plastic dosages, and the chemical nature of waste plastic itself.
- When looking at the types of plastic most suitable for each mixing method (wet or dry), the easiest and most practical way is to simply consider the melting temperature. Typically, plastics with a low melting point, such as PE and PP, will be more suitable for the wet mix process as opposed to high melting point plastics, such as PET and ABS. In the case of wet mixing, plastics having relatively lower viscosity would be more suitable than high viscosity plastics as it would ensure better dispersion in the asphalt binder.
- Apart from rheological issues, the utilization of plastics in asphalt mixture introduces other concerns, such as fuming during construction. In fact, potential negative impacts of such fumes on health (e.g., long-term cellular damage, damage to human DNA, eye and throat infection) have been identified in the referred literature. Studies have also indicated that along with the nature of waste plastic, different external factors such as temperature, wind speed and its direction, presence of sunlight and/or cloud, etc., can influence the degree of impact.
- In addition to fume related health and environmental concerns, leaching of waste plastic particulates and other toxic chemicals have also been identified. In fact, release of contaminants such as Bisphenol A (BPA), Phthalates (particularly available in PET) was found to be responsible for the development and hormonal related issues in humans and animals. The literature further indicates that decrease in temperature and increase in the acidity level of the environment accelerates the leaching of waste plastics. As far as the influence of the mixing method (wet or dry) on leaching potential is concerned, there is no consensus among researchers so far.
- The use of waste plastics in asphalt mixture-related applications introduces several social, environmental, and economic aspects when considering its incorporation into the roadway infrastructure. It is essential to quantitatively evaluate these factors through appropriate and localized life cycle assessment tools to choose the optimal application method and maximize their use.
- In general, encouraging results have been reported for several pilot projects around the world that have looked at the incorporation of waste plastics in asphalt pavement. Therefore, considering the quantity of waste plastic utilized in these field projects, its potential use in large-scale projects can play an important role in contributing to a viable recycling outlet for waste plastic reuse.

8. Recommendations, limitations, and prospects

- It has been recognized that recycling methods for different types of waste plastics will be different due to their unique material attributes, such as melting temperature. For example, the use of chemical treatment for some thermoplastic wastes such as PET has been found to be a promising way to tackle higher melting temperature related challenge. Although different types of chemical treatments (e.g., metanalysis, hydrolysis, glycolysis and aminolysis) have been attempted for thermoplastic wastes, further research is warranted to identify the most efficient chemical treatment approach for such purposes. On the other hand, the use of conventional melting process and chemical treatment has been reported to be unsuitable for thermoset plastic wastes due to their crosslinked structure. Therefore, additional effort is needed to identify the appropriate technology to tackle the challenges associated with thermoset plastic wastes utilization in asphalt mixture.
- While evaluating the mechanical performance of asphalt mixture containing waste plastic is important, it is equally important to understand the associated environmental and health related concerns with the adoption of such technology. Although many of the reported research works have focused on mechanical performance parameters of asphalt mixture containing a wide range of waste plastics, very

limited information is available on associated potential health hazards in terms of fume emission during construction and leaching of waste plastic from the paved roads during their service life. Therefore, it is advised to conduct further research on the environmental and health-related concerns while incorporating waste plastic(s) in asphalt mixture.

- Although few studies have indicated the benefits of using waste plastic in terms of associated environmental impact using LCA analysis, further studies are still required to provide more quantitative data considering different factors such as logistics, types of locally available plastics, and field-based pavement performance data. It is also to be noted that most of the reported studies have utilized simplistic and potentially outdated models; therefore, a more robust analysis using the latest developments is desired for LCA based analysis. Likewise, although the economic benefit of using waste plastic using LCCA based analysis is reported, further analysis using the cradle-to-cradle approach is required considering various direct and indirect costs associated with the collection of waste plastics, treatment of waste plastics, application, performance, and recycling.
- Although several laboratory based research works have shown encouraging results on the successful utilization of waste plastic in asphalt mixture, corresponding evidence related to short term and long term performance parameters on field samples are equally important for the successful demonstration of such technology. Therefore, further research is advised through an evidence based accelerated pavement testing or evaluating samples collected from real field sections (short term and long term) containing waste plastic in asphalt layer(s).

CRediT authorship contribution statement

Prabin Kumar Ashish: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Anand Sreeram:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Investigation, Methodology. **Xiong Xu:** Methodology, Supervision, Writing – original draft, Writing – review & editing. **Pavan Chandrasekar:** Conceptualization, Writing – original draft, Writing – review & editing. **Ajayshankar Jagadeesh:** Conceptualization, Writing – original draft, Writing – review & editing. **Dheeraj Adwani:** Writing – original draft, Writing – review & editing. **Rabindra Kumar Padhan:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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