Feasibility Study on the Use of Multilayer Plastic (MLP) Waste in the Construction of Asphalt Pavements

Aakash Singh, Ambika Behl, and Ashish Dhamaniya

Abstract In the last few years, considerable research has been carried out in the country to determine the suitability of plastic waste in the construction of bituminous roads. That research led to establishing that linear density polyethylene (LDPE) and high-density polyethylene (HDPE)-based plastic waste can be successfully used for road construction, but there is very limited research available on the use of polyethylene terephthalate (PET)-based multilayer plastic waste in road construction. In the present study, an attempt has been made to evaluate the feasibility of using multilayered plastic (MLP) waste in the construction of roads. The properties of asphalt mixes prepared with multilayered plastic (MLP) waste have been studied, and the efficacy of different types of waste plastic for coating the aggregates was also studied. The moisture resistance of MLP-based waste plastic asphalt mixes has also been studied in comparison to PE (polyethylene) plastic waste-based and control asphalt mix. The MLP waste-modified mix showed better stability and resistance to moisture damage when compared to the PE-modified waste plastic mix. The effect of waste plastics in reducing overall bitumen demand in the asphalt mix was also studied. The heating of waste plastic to coat aggregates has always posed a concern regarding air emissions. To address this concern, the environmental emissions were measured during the coating and mixing stage. In this study, an attempt is also made to evaluate the coating of waste plastic on the aggregates using a simple approach of coatability index.

Keywords Multilayered plastic waste · Plastic-coated aggregates · Coatability index · Bitumen · Control mix · Waste plastic mix

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1 Introduction

Plastic consumption in India has grown at a significant pace over the past five years, and so has its plastic waste generation. India produces 3.4 million tonnes of plastic waste in a year. Among the total municipal solid waste, about 4% of waste is plastic, out of which most plastic is generated from households, industries, food packaging, and water bottles. Likewise, a couple of states in India have a waterfront district that creates plastic waste from sports activities on the coastline. Improper loading of such waste collected outside the towns, cities, and villages creates undesirable and tumultuous conditions that influence the soundness of individuals living around it and make landfill issues bring about significant natural ramifications, adding to groundwater contamination. Central Pollution Control Board (Govt. of India) stated in its reports that only 60% of the total plastic waste is collected and recycled in India, and the remaining is uncollected and littered [1]. These wastes are the source of pollution as plastics are non-biodegradable and harmful to the environment for decades. Around 50% of the plastic consumed is used for packaging. The most utilized polymeric materials for packaging are polyethylene (PE)-based carry bags and multilayered plastics (MLP).

Bitumen, a by-product of crude oil distillation, is known for its adhesive properties, and it is used as a binding material in road construction. Bitumen is a visco-elastic material; it is brittle and hard in a cold environment and soft in a hot environment. Due to this behavior, the performance of these bituminous binders has been questioned many times [2]. To produce hot mix asphalt for road construction, the bituminous binder is heated up to 150–160 °C and coated over hot aggregates and then rolled. Environmental factors such as temperature, air, and water have a profound effect on the durability of bituminous mixtures. Longer exposure of pavements to water causes loss of adhesion at the bitumen–aggregate interface, which leads to moisture damage in pavements. The bituminous mix's resistance to moisture damage can be increased by using anti-stripping agents as additives, but they have limited use, and the process also increases the cost of road construction [3]. Polymer-modified binders are also recommended to be used for better moisture resistance of the asphalt mix. The use of waste plastic in the preparation of asphalt mixes has shown improved Marshall stability strength, fatigue life, reduction in overall rutting, and reduced low-temperature cracking of the bituminous surfacing [4]. Most of the waste plastics coming from the packaging industry are polyethylene-based and do not cause the release of any harmful gas at 1300C–1400C, and at this temperature, plastic is in the molten form, having an excellent binding property. The addition of waste plastics improves the stability, tensile strength, stiffness, void characteristics, and moisture resistance of bituminous mixtures [5].

Plastics mainly used for packaging are made up of polyethylene, polypropylene, and polystyrene, and their melting point varies from 1300 to 2000C. In the dry process, the shredded waste plastics tend to form a film-like structure over the aggregates when sprayed over the hot aggregate ranging 1500–1700C. Plastic-coated aggregates are better raw material for the construction of flexible pavement. Plastic-coated aggregates are mixed with hot bitumen as per the requirement of the mix, and the mixes are used for road construction. The evaluation of the waste plastic asphalt mix was done, and it was found that the waste plastic asphalt mix showed improved binding property and moisture resistance. The waste plastic mix showed improved Marshall stability value in the range of 18kN–20 kN, and the load-bearing capacity of the road is increased by 100% [6]. Another study investigated the performance of asphalt mixtures containing recycled polypropylene and found that mixes with the addition of recycled plastics showed improved physical and mechanical characteristics and provided a sustainable solution for the disposal of such waste [7]. As per IRC: SP: 98 [8], 6−8% of plastic waste (mainly PE and PP) by weight of bitumen can be used in asphalt road construction. A study was carried out to evaluate the effect of the addition of polyethylene-based waste plastic in the mix by using a dry process, and it was concluded that by adding polyethylene in the mix, aggregates exhibit better engineering properties, and the waste plastic asphalt mixture showed increased fatigue resistance, reduced permanent deformation, and also provided better adhesion between asphalt and aggregates [9].

In another study, it was observed that for stone mastic asphalt (SMA), the addition of shredded waste plastics could be used instead of stabilizers to control the drain down and enhance the performance of SMA mixtures [10]. A study for the comparative performance of shredded waste plastic asphalt mix and polymer-modified bitumen asphalt mixes was carried out, and the shredded waste plastic (SWP) was used instead of other stabilizing additives to prepare the SMA mixture. It was concluded that waste plastic in suitable dosage could be recommended in SMA [11]. Polythene fibers and waste plastic bottles (polyethylene terephthalate) were observed to be effective in SMA in retarding the drain down of bitumen and mineral filler [12]. Research also showed that coating of shredded waste plastic over the hot aggregates provides the mixture with better strength and performance [13, 14]. In most of these studies, PE (polyethylene)-and PP (polypropylene)-based waste plastics were used. Indian Road Congress (IRC) SP 98:2013 code also allows the use of PE-PP-based waste plastic in asphalt roads but multilayer plastics (MLPs) have not been studied in much detail.

Multilayer Plastic (MLP) is plastic with at least one layer of plastic as the main ingredient combined with one or more layers of materials such as paper, paper board, polymeric materials, and aluminum foil. The plastic component can be polyethylene terephthalate (PET), polypropylene (PP), or polystyrene (PS). Recycling MLPs is challenging, and the only way to process them to get rid of this waste is by incineration. Most of the MLPs (multilayered plastics) contain polyethylene terephthalate (PET) including other olefins, and their melting point is in the range 150−240 °C. To overcome the challenges of waste plastic management, especially MLP waste, the authors have explored the feasibility of incorporating MLP plastic waste in asphalt road construction. The properties of asphalt mixes prepared with multilayered plastic (MLP) waste have been studied and the efficacy of different types of waste plastic for coating the aggregates was also studied. The moisture resistance of MLP-based waste plastic asphalt mixes was studied in comparison to PE waste-based and control asphalt mixes. One of the major concerns in using waste plastic in road construction is whether the waste plastic is able to coat the stone aggregate or not. If a particular type of waste plastic is not able to coat the aggregates, then it will be present in the asphalt mix as a foreign material and hamper the performance of the asphalt mix. It is very difficult to evaluate the coating of waste plastic over stone aggregates with the naked eye, and expensive test instruments like scanning electron microscope (SEM) are required to confirm the coating of plastics over aggregates. Field engineers often don't have instruments like SEM available on site to check the coating of waste plastics on aggregates. The authors in this study have employed an easy method to evaluate the coating of waste plastics over aggregates in the field.

2 Materials Used

The coarse aggregates (10 and 20 mm NMAS) and fine aggregates (stone dust, lime powder) were obtained from a local quarry in compliance with the Bureau of Indian Standards (BIS) code [15]. VG-30 bitumen (viscosity-graded binder) conforming to IS: 73 [16] was procured from an Indian refinery (Indian Oil Corporation Limited).

2.1 Waste Plastics

In this study, three different types of waste plastics were used in the shredded form: MLP 1, MLP 2, and Polyethylene (PE)-based waste plastic (carry bags). MLP 1 contains 100% PET-based multilayered plastic (polyethylene terephthalate), whereas MLP 2 contains a combination of PET (polyethylene terephthalate) and PP (polypropylene) plastic. All three types of waste plastics were shredded up to 2−5 mm size, after proper cleaning and washing and were used at 3 different dosages in this study, i.e., 6, 8, and 10% by weight of the bitumen. The properties of waste plastics are illustrated in Table 1.

Table 1 Properties of waste plastic

S. No	Description	Tm, °C	Tc, °C	Findings
1	MLP 1	253.9	198.1	PET
2	MLP 2	158.5	117	PP and PET
3	PE	122.2	108.5	LLDPE/LDPE

Crystallization temperature (Tc), and melting temperature (Tm)

2.1.1 Characterization of Waste Plastics

The thermal behavior and constituents of plastics were studied using Differential Scanning Calorimeter (DSC). The thermal analysis was done to determine the crystallization temperature and melting temperature of the plastics. The instrument used was Mettler Toledo DSC. Table 1 shows the thermal properties of the plastics used in the study.

3 Experimental Program

3.1 Characterization of Asphalt Mixes

The bituminous mixes were prepared using the Marshall mix design procedure. The bituminous mixes prepared with the varying dosage of waste plastics were tested for Marshall parameters, ITS, TSR, resilient modulus, and dynamic creep. All the tests were done for 3 replicates, and the results reported are average. The results of waste plastic mixes were compared with the conventional unmodified bituminous mix. The samples for the evaluation of susceptibility to moisture damage were prepared at $7 \pm 1\%$ air voids. The moisture susceptibility of the bituminous concrete mixes with waste plastics was evaluated by measuring the tensile strength ratio (TSR) as per ASTM: D6931−12. The indirect tensile strength (ITS) of the mix is determined before and after conditioning of Marshall specimens, and the tensile strength ratio (TSR) is then calculated as the ratio of the original strength and retained strength after accelerated moisture conditioning.

Resilient Modulus is an important parameter to evaluate the performance of a mix and to assess the pavement response to traffic loading. All the specimens for the resilient modulus test were prepared at 5% air voids. The specimens were tested at 25, 35, and 45 ºC in accordance with ASTM: D7369−11 after their conditioning at the selected test temperature for 6 h. Repeated haversine load with a loading time of 0.1 s and a rest period of 0.9 s was used in all resilient modulus tests. The uniaxial repeated-load creep test was carried out to assess the rutting performance of control and modified asphalt mixtures. It was carried out in accordance with European standards [17]. A universal testing machine (UTM) was employed to assess the asphalt mixture's permanent deformation. A cyclic stress of 450 kPa, having a haversine waveform with a loading period of 0.1 s followed by a rest period of 0.9 s was applied during the test, and total accumulated strain (%) was recorded. Before conducting the test, all specimens were kept under a controlled temperature chamber for three hours to reach a uniform temperature of 60 °C. A seating stress of 10 kPa was applied to ensure positive contact between the loading plate and the specimen. The results of waste plastic mixes were compared with the conventional unmodified bituminous mix.

3.2 Effect of Waste Plastic Coating on Aggregates

Washed and dried aggregates were heated to a temperature of 200 °C for 2 h. Then shredded waste plastic was uniformly spread over the hot aggregate, ensuring that piling of plastic waste did not occur. A mix of plastic and aggregates was prepared in a Hobart mixer at 160−155 °C. The plastic-coated aggregates were cooled to room temperature and then evaluated for water absorption [15]. These plastic-coated aggregates were also evaluated for aggregate impact value (AIV) to check the effect of different types of waste plastics on aggregate strength. Velasquez et al. [18] and Bairgi et al. [19] used the coatability index to evaluate the coating of warm mix asphalt over aggregates. In this study, the same approach was used to check the coating of waste plastic over the aggregates. Coatability Index was calculated by using Eq. 1. Further, this coatability index is then co-related with the moisture susceptibility of the mix, i.e., tensile strength ratio. Figure 1 shows the different types of plastic-coated aggregates and control aggregates:

$$\text{Coatability Index} = \frac{\mathbf{Ao - Ac}}{\mathbf{Ao}} * 100 \tag{1}$$

where

Ao = Water absorption of control aggregates.

Ac = Water absorption of coated aggregates.

It can be observed from Fig. 1 that with the naked eye it is very difficult to find out the coating of waste plastics on the aggregate surface.

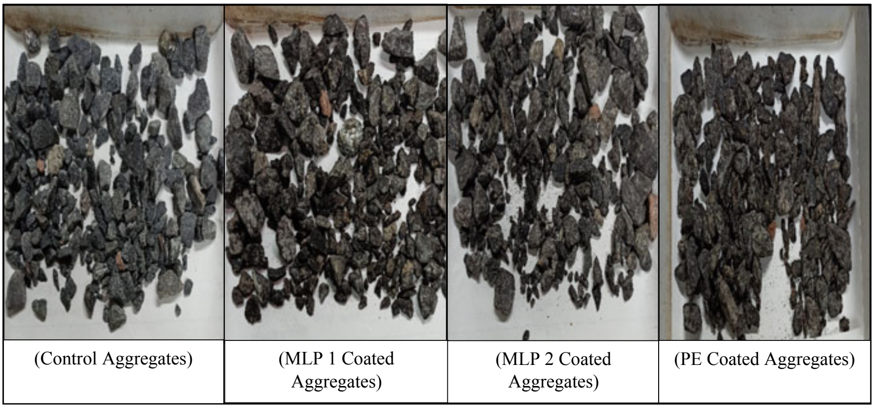

Fig. 1 Control aggregates and aggregates coated with different types of plastics

Fig. 2 DS1IAQ probe

3.3 Emission Measurement

Recycling and reusing of waste plastic in road construction can significantly contribute to saving the environment but there have been concerns across the globe about the release of harmful emissions when these waste plastics will be heated at a temperature of 160–170 °C to prepare hot asphalt mixes. To address these concerns in this study, an attempt has been made to study the emission release during the preparation of hot asphalt mixtures.

In this study, the emissions were recorded at two different stages: during the coating of waste plastics on the aggregates and during the mixing of bitumen with the plastic-coated aggregates. The emissions were recorded in the laboratory using the DS1IAQ probe (Fig. 2). The emissions recorded were total volatile organic compound (TVOC), formaldehyde (HCHO), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen dioxide (NO_2). At the same time, other gases such as nitric oxide (NO) and sulfur dioxide (SO_2) were recorded as zero concentration, thus not reported.

4 Results and Discussion

4.1 Aggregate Characterization

The aggregate impact value (AIV) significantly decreased with the addition of waste plastics. The brittleness of aggregates is measured through the impact value test; coating of waste plastics over the aggregates reduces the voids and air cavities present in the aggregate. The thin film of waste plastics formed over the aggregate surface

Table 2 Effect of waste plastic coating on aggregates' impact value

Mix type	Plastic content (in %/Weight of binder)	Specific gravity	Aggregate impact value
Control mix	0	2.80	8.95
MLP 1	6	2.78	7.530
	8	2.82	6.650
	10	2.80	6.210
MLP 2	6	2.75	5.030
	8	2.78	4.620
	10	2.81	3.890
PE-based	6	2.80	6.080
	8	2.83	5.350
	10	2.79	4.920

resists the cracking of aggregates. It can be observed from Table 2 that with the increase in the waste plastic content, the impact value reduces; it implies that with an increase in the thickness of the coating, the toughness of the aggregates increases. The AIV of control aggregates improves from 8.95 to 6.2 with 10% of MLP 1 waste plastic and to 3.89 with 10% of MLP 2, whereas with 10% of PE waste plastic it improves up to 4.9. MLP 1 waste showed the lowest effect on the AIV of aggregates.

Since MLP 1 primarily contains PET, its melting temperature is around 250 °C, and its glass transition temperature is around 70 °C [20, 21]. The aggregates are coated at 160 °C and at this temperature MLP 1 is in a semi-solid state; the liquid part partially coats the aggregate and gets absorbed into the voids of aggregates, and the solid part gets stuck to the irregular surface of the aggregate. During impact load, the MLP particles absorb some energy due to which the AIV value of MLP 1 coated aggregates is lower than the control aggregates.

4.1.1 Coatability Index

The coating of plastics fills the voids of aggregates due to which the porosity of the aggregates decreases [22]. With lesser voids on the aggregate surface, the absorption of moisture reduces. Table 3 shows that with the addition of waste plastic, the water absorption of the aggregates reduces. Figure 3 shows the trend of coatability index with varying types and percentages of waste plastic content. It was observed that with the increase in waste plastic content, the coatability index of aggregates increased. PE-based waste plastic provided the maximum coating followed by MLP 2 and then MLP 1 coated aggregates. Generally, the water absorption should be less than 2% for an aggregate to be used for asphalt road construction. Higher water absorption will

Table 3 Water absorption and coatability index of aggregates

Plastic type	Plastic content	Water absorption	Coatability Index
Control mix	0	1.597	0.00
MLP 1	6	1.300	18.59
	8	1.160	27.38
	10	0.864	45.89
MLP 2	6	1.062	33.50
	8	0.863	45.96
	10	0.729	54.35
PE-Based	6	0.788	50.68
	8	0.476	70.17
	10	0.233	85.42

result in the stripping of bitumen and will lead to pothole formation and moisture failure in the pavement. The presence of water is detrimental to the adhesion between the bitumen and aggregates.

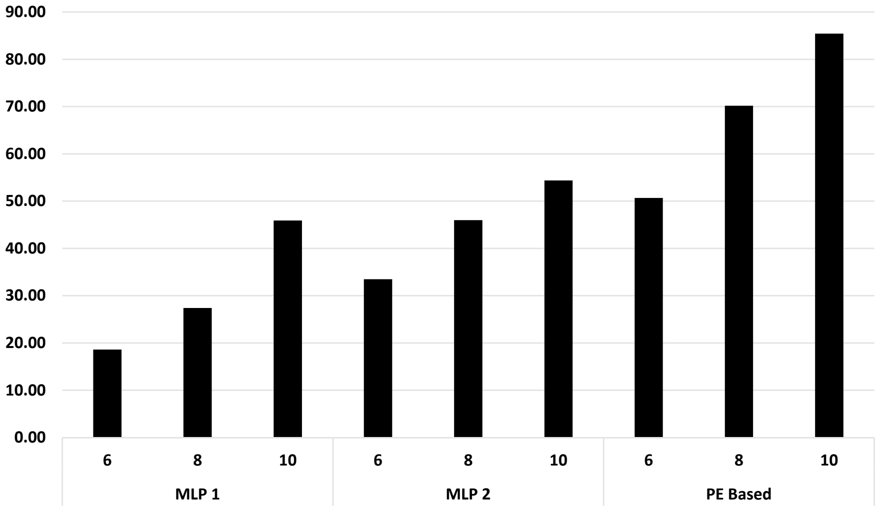

Fig. 3 Coatability index of plastic-coated aggregates

4.2 Marshall Test Results

4.2.1 Effect of Waste Plastic on Optimum Binder Content

It was observed from Table 4 that the optimum binder content decreases with the addition of waste plastic; this is because the plastic is coated over the aggregates, and the plastic gets absorbed by the aggregate and a thin film of plastic is formed. The film fills the pores of the aggregates, which are present at the surface of the aggregates; thus, there is lesser absorption of bitumen over the surface of plastic-coated aggregates, and the effective binder requirement reduces. Hence, a reduction in the optimum binder content of the mix was observed. Mixes prepared with PE-based waste plastic showed the least optimum binder content followed by MLP 2-based mix and then the mix prepared with MLP 1. With the addition of MLP 1 in the mix, there is nearly 2.5% reduction in optimum binder content when compared to the control mix, whereas this reduction increases with the addition of PE waste plastic in the mix to around 3% and with the addition of MLP 2 there is around 2.75% reduction in optimum bitumen content. The optimum bitumen content reduces further with the increase in the plastic content and by changing plastic type.

4.2.2 Marshall Stability and Flow Value

The Marshall stability value is the load required by the specimen to attain failure and it is the measure of cohesion. From Fig. 4, it was observed that the Marshall stability value increased with the addition of waste plastic. At higher waste plastic content, i.e., at 10% there was a reduction observed in the Marshall strength of the mixes. This happened due to the increased film thickness of the waste plastic over the rough surface of aggregates which lead to the reduction in the internal friction between the aggregates, thus the stability of the mix decreases. Also, the addition of very high dosages of waste plastics tends to make the bituminous mix very stiff and brittle. PE-based mixes showed the highest Marshall stability values in comparison to MLP-based mixes. For an effective asphalt pavement, the flow value should be in the range of 2–5 mm [23]; the flow value is the measure of deformation undergone by the sample; it is the vertical distortion at the time of failure. The results obtained from the waste plastic mixes are within the tolerance value.

4.2.3 Marshall Quotient

Marshall quotient is the pseudo stiffness that measures the resistance to permanent deformation of the mix. The Marshall quotient is defined as the ratio of the Marshall stability value and flow value. Its values are found within the tolerance limit at 8%

Table 4 Marshall mix design results

Mix properties	Control mix	MLP 1			MLP 2			PE-Based		
Waste plastic content	0%	6%	8%	10%	6%	8%	10%	6%	8%	10%
OBC%	5.545	5.440	5.408	5.385	5.412	5.375	5.376	5.410	5.288	5.315
Vv%	4.271	4.331	3.887	4.237	3.726	3.641	4.254	4.009	4.092	3.779
Stability (KN)	10.68	13.11	14.22	13.52	14.46	15.46	14.59	14.84	15.78	15.45
Flow (mm)	3.240	3.270	3.148	3.091	3.281	3.165	2.784	3.180	3.116	2.550
Marshall quotient	3.298	4.008	4.516	4.375	4.407	4.884	5.240	4.666	5.064	6.058

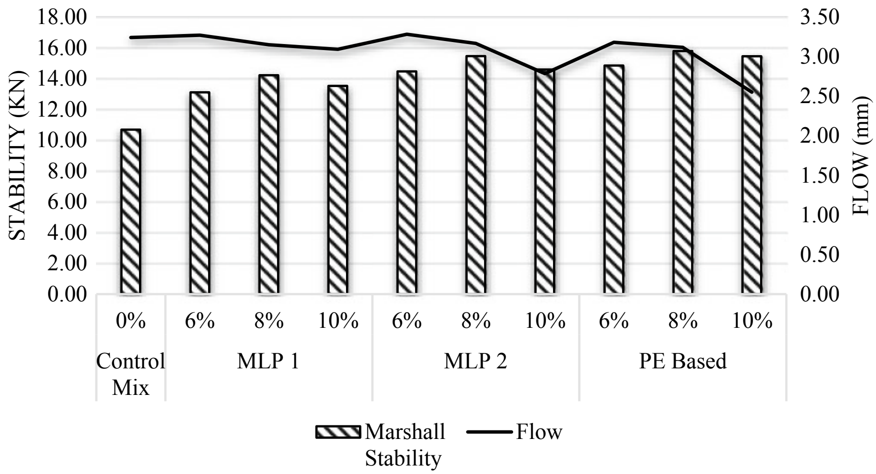

Fig. 4 Marshall stability and flow value

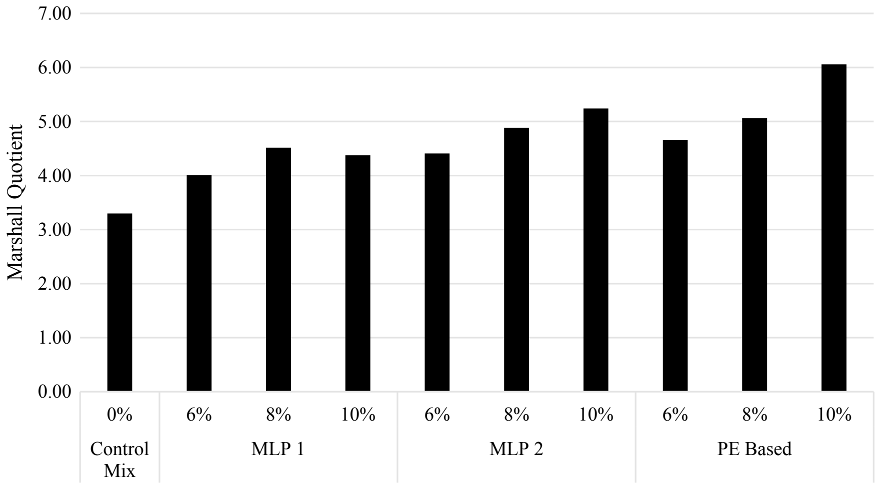

Fig. 5 Marshall quotient

dosage of waste plastic content. From Fig. 5, it was observed that the mix containing PE waste plastic is most stiff among other mixes, followed by MLP 2 mix and then MLP 1 mix. The results obtained from the study show that the mixes containing waste plastic have more resistance to permanent deformation when compared with the control mix; this is due to the coating of waste plastic on the aggregates which leads to a stronger bond between the aggregate and bitumen. It has been observed that with an increase in the percentage of waste plastic in the mix, the thickness of the coating also increases, which makes the mix stiffer; the chemical properties of the plastics also play an essential role in determining the stiffness of the mix. From the volumetric parameters of plastic waste-modified mixes, it can be concluded that a dose of 8% waste plastic by weight of bitumen should be considered as optimum plastic content.

4.3 Indirect Tensile Strength and Tensile Strength Ratio of the Mix

The indirect tensile strength test is appreciated in assessing the tensile properties of the asphalt mixes, which can be correlated with the cracking of the pavement. A high value of indirect tensile strength is an indication of higher resistance to low-temperature cracking. Moreover, a higher value of indirect tensile strength at failure would imply that the asphalt mix can withstand larger tensile strains prior to cracking. The tensile strength ratio of the mix is used to evaluate the susceptibility of the mix to moisture damage. Figure 6 shows the variation in indirect tensile strength and tensile strength ratio with respect to varying types and dosages of waste plastic. The indirect tensile strength of the mix increases with the increase in waste plastic content and at 10% dose of waste plastic, there is a slight decrease in the ITS value. This might be because with the increase in waste plastic content, the thickness of the coating of plastic over the aggregates increases, making the mix brittle, thus it reduces the resistance of the mix to tensile strain. From Fig. 6, it was observed that the mixes containing plastic waste showed more ITS value when compared with the control mix. Among the waste plastic mixes, the PE-based mix offers maximum ITS value followed by MLP 2 and then MLP 1.

The tensile strength ratio of the mixes containing waste plastic is found higher. The presence of waste plastic in the asphalt mix increases the resistance of the

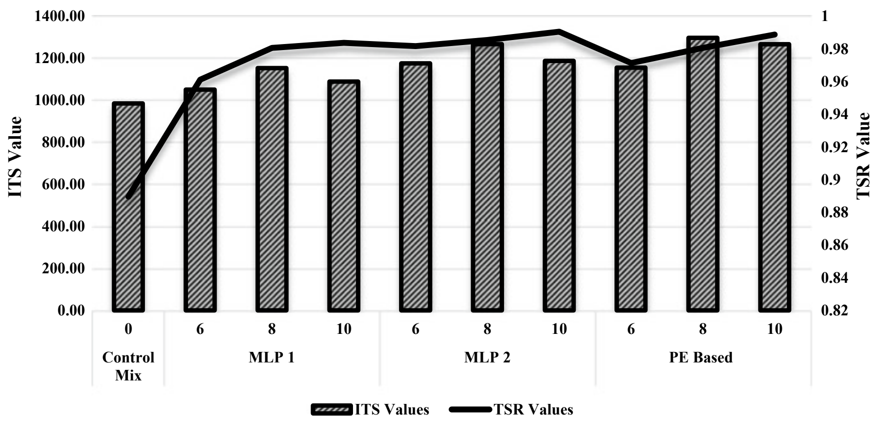

Fig. 6 ITS and TSR results

asphalt mix toward moisture damage. MLP 1, MLP 2, and PE are polymers with long-chain hydrocarbons, and bitumen is a complex mixture of saturates, aromatics, resins, and asphaltenes which are also hydrocarbons. When hot bitumen is added to waste plastic-coated aggregates to prepare asphalt mixture, some portion of bitumen diffuses through the plastic coating and makes a strong bond with the aggregate. This results in a stronger bonding between the bitumen and plastic-coated aggregates and hence imparts better resistance to moisture penetration into the mix.

4.4 Coating and TSR Correlation

From Fig. 7, it was observed that with the increase in the coating of waste plastics over the aggregates, the resistance to moisture damage has increased significantly. This shows that the coating of plastic has a positive correlation with the tensile strength ratio of the mix. The coating of plastic over the aggregates was evaluated using the coatability index. It was observed from Fig. 7 that the coatability index positively correlates with the TSR values of all three waste plastic mixes. As the coatability index can be directly calculated with the water absorption of the aggregates, thus, it can be easily calculated on-site in the field. In earlier studies, researchers have evaluated the coating of plastic by using X-ray diffractometry, which requires a dedicated instrumental setup and trained personnel to operate the instrument and which is also not available easily in civil engineering labs across the country. Thus, the coatability index test will find its usefulness for evaluating the coating of waste plastic in situ.

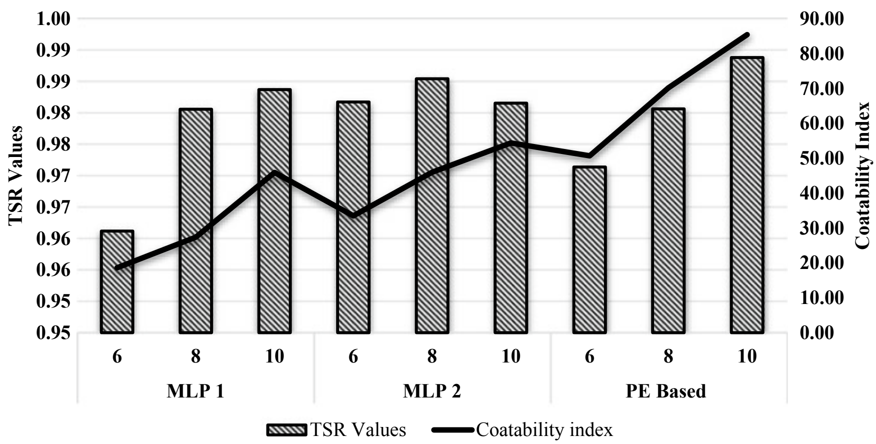

Fig. 7 TSR and coatability index correlation

4.5 Environmental Emissions Measurement

Table 5 shows the results of gaseous emissions during the coating of waste plastics over aggregates. It was observed that the concentration of total volatile organic compound (TVOC) during the mixing of MLP 1 was highest, followed by MLP 2 and then the PE-based mixture; due to the presence of PET and PP in MLPs, the concentration of TVOC was higher. The melting temperature of PET is around 250 °C; hence, the MLP 1 plastic was partially melted at a coating temperature of 160–165 °C; thus, the release of formaldehyde was lesser for MLP 1 mixtures. Carbon dioxide emission was observed highest for MLP 1 and least for MLP 2 mixtures.

Table 6 illustrates the results of the emission of gases during the mixing of bitumen with plastic-coated aggregates. It was observed that the emissions for the asphalt mixtures containing waste plastics were higher than the control mixture. Mixtures modified with MLP 1 showed the highest emissions of TVOC, CO_2, and the least emission of formaldehyde. In contrast, emissions of NO_2 and CO are nearly similar for all the mixtures.

4.6 Resilient Modulus

The resilient modulus of waste plastic-modified mixes was evaluated and compared with the resilient modulus of control asphalt mix at different temperatures. To understand the effect of the addition of different types of waste plastics on asphalt mix properties, it is imperative to understand the properties of basic polymers present in these waste plastics. MLP 1 contains Polyethylene Terephthalate (PET) polymer and MLP 2 is a combination of Polypropylene (PP) and PET, whereas PE-based waste is basically waste carry bags which is mainly LDPE. All three polymers PP, PE, and

Table 5 Emissions during coating of plastic

	TVOC (ppm)	HCHO (ppm)	CO (ppm)	CO_2 (ppm)	NO_2 (ppm)
MLP 1	1.26–1.33	0.09	011–024	590–650	0.25–0.29
MLP 2	1.18–1.21	0.11	05–017	523–580	0.23–0.28
PE-based mix	1.12–1.18	0.13	011–025	546–585	0.22–0.28

Table 6 Emissions during mixing

	TVOC (ppm)	HCHO (ppm)	CO (ppm)	CO_2 (ppm)	NO_2 (ppm)
Control mix	1.04–1.07	0.07	07–019	535–572	0.18–0.26
MLP 1	1.25–1.43	0.11	015–025	593–736	0.25–0.32
MLP 2	1.11–1.31	0.12	018–027	578–682	0.26–0.30
PE-based mix	1.15–1.23	0.13	018–028	568–597	0.26–0.32

PET have good moisture barrier properties; out of the three, PE is a more flexible polymer in comparison to PP and PET. PET is a long-chain thermoplastic resin made from ethylene glycol and terephthalic acid. During the manufacturing of food packaging material, PET is held in the stretched form at elevated temperatures, it slowly crystallizes and becomes more rigid and less flexible. PET is a semi-crystalline resin [24, 25]. When added to the asphalt mixture, it stiffens the mixture and increases the M_R value in comparison to the control mixture. However, due to its high melting point (250 °C), PET is not able to coat the aggregates completely and is present in the asphalt mix as inert material and hence it absorbs some energy resulting in larger recoverable deformation thus reduced resilient modulus values in case of MLP 1. MLP 1 has 100% PET content, whereas MLP 2 has both PP and PET due to which the MLP 1 modified mixture has lower M_R values when compared with MLP 2 and PE-based mixture.

The findings of this study reveal that the presence of waste plastics increases the rigidity of the mixture to a certain extent because the addition of these additives decreases the stresses caused by cyclic loading due to their elastic response. The increase in M_R values at 25 °C from the control mixtures are 19, 22.62, and 30.14% with the addition of MLP 1, MLP 2, and PE waste plastic respectively, whereas at 35^0C the increase observed was 41.45, 56.94, and 54% with the addition of MLP 1, MLP 2, and PE waste plastic respectively, and at 45 °C the increase observed was 22.29, 26.11, and 15.28% with the addition of MLP 1, MLP 2, and PE waste plastic, respectively. In the previous investigations carried out by other researchers, it was found that the stiffer asphalt mixes show lower permanent deformation under dynamic loading [26, 27]. Another study done by Tayfur et al. on different polymer modifiers showed that the stiffer mix undergoes higher permanent deformation under static loading and lesser permanent deformation under dynamic loading [28]. Since the stiffness of the mixture increases with the addition of waste plastic, the resistance to permanent deformation of the mixture's containing waste plastics as modifiers increases (Fig. 8).

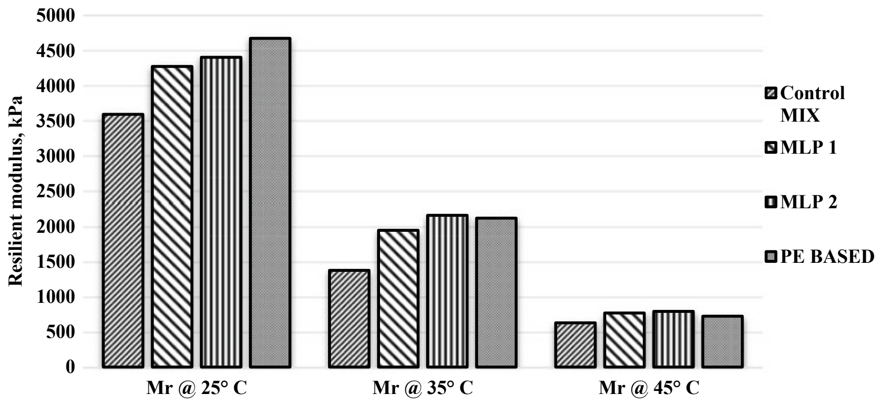

Fig. 8 Resilient modulus of the mixes

4.7 Dynamic Creep Test

Total permanent deformation of waste plastic asphalt mixes was found by doing a dynamic creep test, and results were compared with the control asphalt mixture. The specimens for the dynamic creep test were prepared at optimum waste plastic content (8% by weight of bitumen). It can be observed from Fig. 9 that with the addition of waste plastics, the rutting resistance of the asphalt mixtures has improved significantly. PE-modified mixes result in the lowest amount of permanent deformation, followed by MLP 2 modified mix and MLP 1 modified mix. MLP 2, which contains both PP and PET, showed more resistance to permanent deformation when compared with MLP 1 which is 100% PET. PP is referred to as amorphous and PET is referred to as a semi-crystalline substance. When the coating and mixing temperatures exceed the glass transition temperature of PET (75 °C), the amorphous portion of PET and PP transforms into a liquid; and due to PET's high melting point of roughly 250 °C, a crystalline region exists as a solid part. As a result, MLP 2 shows improvement in asphalt mixture properties in two ways: first, the liquid and molten part of MLP 2 increases the binding between the asphalt binder and aggregate, and second, the solid part of MLP 2 absorbs some of the cyclic load's energy.

From Fig. 9, it was observed that after 1000 loading cycles the deformation observed in the control mix was maximum, whereas the mixture modified by PE waste plastic was minimum and it is 63.33% lesser than the control mix followed by MLP 2 modified mixture which is nearly 40% lesser than control mix and mixture modified by MLP 1 shows 20% lesser deformation than control mix. MLP wastes due to their high melting point and rigid structure do not melt and coat the aggregates completely and hence showed more deformation in comparison to PE-based waste plastic mix. PE polymer is more flexible than PP and PET plastic.

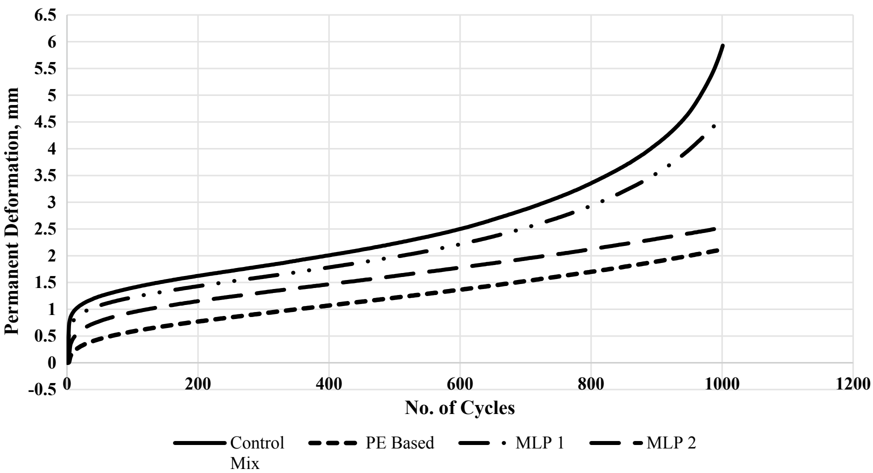

Fig. 9 Cumulative permanent deformation versus load cycles at 60 °C

5 Conclusion

Waste plastic can be blended with aggregate or mixed with bitumen to change its property. Most of the available studies are limited to the use of polyethylene (PE) and Polypropylene (PP)-based waste plastic. The laboratory investigation on multilayer plastics has been attempted in the present study, and the following conclusions can be drawn on the basis of the results achieved in this study:

1. Coating of waste plastics over aggregates improves the strength as well as water absorption of aggregates. PE-based waste plastic having a melting point of 122 °C gives the highest coating on aggregates when asphalt mixes are prepared at 155–160 °C.
2. With the addition of waste plastics, the optimum bitumen demand of the asphalt mixes decreases, which leads to the saving of natural resources of petroleum-based bitumen.
3. From the Marshall quotient values, it can be concluded that the stiffness of mixes increases with the addition of waste plastics. 8% dosage is found as the optimum waste plastic content. At higher dosages, the asphalt mix becomes very stiff which can lead to cracking failure.
4. MLP-based waste plastic has rigid polymer (PET), due to which mixes containing MLP waste plastic give higher resilient modulus since the stiffness in the mix has increased.
5. From dynamic creep results, it can be concluded that PE being a flexible polymer gives better resistance to permanent deformation as the flexible PE allows the recovery of the strain. In colder regions where cracking failure is of concern, PE-based waste plastic should be used.
6. The addition of waste plastics improves the resistance of asphalt mixes to moisture damage.
7. Coatability Index is a good parameter to evaluate the coating of waste plastic over the aggregates.
8. Emissions for mixtures containing waste plastics were observed higher than the control mixture; among them, the mixture containing MLP 2 and PE waste plastics have nearly similar emissions.

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