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The impact of polyethylene terephthalate waste on different bituminous designs

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Abstract

To lessen the harmful impact of waste products on the environment and nature, it seems reasonable to introduce a method of reuse of waste materials in engineering projects and construction projects, for example, road construction to enhance the asphalt mixture qualities. Pavement made with different modified bitumen binders is used to aid in resistance to cracking and permanent deformation. Decomposed waste like polyethylene terephthalate (PET) has been successfully used to modify bitumen production. This study assessed the bitumen PET waste's integrity with conventional tests such as penetration, softening point, viscosity, flash and fire point, and ductility tests. Based on the changes in the bitumen results, PET waste proportions of 8%, 10%, and 12% by weight of bitumen content were compared to semi-dense bituminous concrete (SDBC), dense-graded bituminous macadam (DBM), and bituminous macadam (BM). The consistency of bituminous concrete is measured using Marshall values. The PET-modified mixture was found to be more resistant to deformation than the conventional sample, and the rate of deformation in the PET-modified mix was lesser than in the conventional mix.

Keywords: Bituminous mix design, PET (poly-ethylene terephthalate) waste, Marshall design, Flexible pavement, Modified bitumen

Introduction and background

Today, it seems difficult to imagine the complete absence of manmade organic polymers or plastics. However, their widespread development and use dates only from 1950 [1]. Plastics are various forms of synthetic or semi-synthetic materials that are used in a wide variety of products. Plastic production has grown at an unprecedented rate, outpacing that of any other human-made commodity [2, 3]. As reported in the Paris Climate Agreement, the key concern has recently been to improve plastic design and production to make reuse, repair, and recycle easier, to keep the plastic production away from fossil fuels, and to cut greenhouse gas emissions [4]. Petroleum and natural gas are used in the production of many synthetic plastics today [5]. The most dangerous application of plastics, aggravated by the global shift from recycled to single-use goods. In high- and middle-income countries, the proportion of plastic in urban solid waste increased from 1 to 10% between 1960 and 2005 [6]. The plastic is widely regarded as one of the most important technological innovations of this time span. It has outstanding characteristics such as low costs, high reliability, low-density durability, high strength-to-weight ratio, and ease of operation and shaping [7, 8]

Plastic demand has increased significantly, and by 2050, it is expected to reach 34 billion metric tonnes [1]. The packaging industry accounted for 42% of plastics manufacturing in India, followed by construction (14%), consumer products (24%), industrial goods (13%), and other 7% [9]. While the production of plastics in all of their types cannot be prevented, recycling could be a better option for disposing of hazardous waste plastics that damage the environment [10–12]. Millions of tonnes of plastic waste are produced each year in various forms around the world. Almost a quarter of all plastic waste is recycled and reused in various fields. Plastic recycling and regeneration, on the other hand, are insufficient, with millions of tonnes disposed of in landfills and the rest of the world finding their way into soil, seas, and rivers every year [13]. This percentage of recycled plastic can be increased by turning waste plastic into useful housing and construction materials [14]. Plastics can be used in a number of applications. Some plastics, such as plastic bottles, are only used for a brief period of time before they are discarded. After collecting plastics from customers or plants, recycling plastic is the preferred option because plastics can be recycled several times. The majority of plastic bottles gathered from the household garbage stream for recycling, according to the Waste and Energy Action Programme (WRAP) report, are plastic bottles. The bulk of bottles are created from polyethylene terephthalate (PET), which accounts for 55–60% of all bottles Waste and Resources Action Programme [15]. PET is chosen in the soft-drink container or plastic bottle industry because it is rugged (so that it can survive being dropped), inexpensive, clear, durable, and odor-resistant and has a low carbon dioxide permeability. PET is also used in electrical insulation, photographic, decorative film laminates, and magnetic tape [16]. PET recycling has not been done in the same quantity as PET processing [17, 18]. To optimize the life management end of service efficacy of waste PET bottles, new application areas should be explored. The use of waste PET as a road pavement additive for bitumen may be a promising research field for extending end-of-service life. PET waste was widely applied to bituminous mixtures using the dry method, i.e., used as aggregate in bituminous mixtures, in order to boost the efficiency of road pavements in previous studies. Researchers discovered that when PET waste was utilized as a bitumen-adjusted, permanent deformation, stiffness, fatigue life, and Marshall stability were increased [19–21]. Unlike the previous studies, depending on the bitumen and additive concentrations, a bitumen binder was changed with an addition produced from PET waste via an aminolysis and glycolysis process, which increased Marshall stability and moisture resistance [22]. Concrete technology was used to test the efficiency of PET as an aggregate substitute. Boutemeur et al. [23] investigated the use of PET as aggregate for concrete in Algeria. The use of waste PET granules pellets as a partial fine aggregate substitute in asphalt mixtures has been investigated [20]. Recycled plastic waste aggregate was created from discarded plastic bags and then utilized in an asphalt mix [24]. When 12% PET crushed by a total bitumen weight was pre-heated up to 300 °C, and used on the aggregates, a 5.1% mix design shows that the Marshall Quotient has increased massively compared to a standard limestone mixture of 5.9 percent bitumen [25]. Furthermore, Ahmadinia et al. [26] discovered that PET, which makes up 6% of the total weight of the bitumen and can pass through a sieve of 1.18 mm during the dry process increases the

Marshall value by 25% more than granulated asphalt, which is composed of crushed aggregate and 6% of aggregates.

When comparing the properties of stone mastic asphalt with different percentages of waste PET as an additive to a typical mixture, the following results were obtained: asphalt mixtures containing 0.2% PET have a 5% higher stiffness. An asphalt mixture of 1% PET has a fatigue life of 124.8% longer. At 450 kPa, the fatigue life of an asphalt mixture containing 1% PET is 60% longer [27]. The following was the result of using recycled PET instead of a conventional mixture: adding recycled PET to asphalt mixtures has no effect on the stiffness of the asphalt properties. Adding 20% recycled PET to an asphalt mixture resulted in 40% less deformation (by total weight of bitumen) [21]. For certain applications, virgin PET is the best choice. Good tensile strength, fair thermal stability, chemical resistance, processing capability, color capability, and clarity are just a few of the advantages of this material [28]. At normal temperatures and pressures, it can be shaped. PET can be made from petroleum hydrocarbons by reacting ethylene glycol with terephthalate acid [29]. Tunde, Alaro, and Adewale [30] boosted the bitumen's viscosity, softening point, and flash & fire points, and lowered its penetration and ductility. Increased adherence of asphalt mixture was produced by increased softening point and decreased penetration [31]. Using the dry method [22], adding PET to the mixture improved the softening point as well as decreased penetration. The resistance of the binder to heating increased when the softening point was increased [32]. Marshall stability demonstrates the pavement's capacity and resilience against rutting. Similar findings were achieved when PET was introduced to asphalt mixture in tests focused on the impact of PET wastes on the Marshall stability of asphalt mixture. First, when a particular amount of PET was applied to the asphalt mixture, the stability improved and further PET was incorporated to the mixture, the stability began to deteriorate [22, 33–35]. As stated by Ameri and Nasr [33], Marshall stability was increased to its highest value simply adding PET upto 10% of the binder weight, and subsequently, the Marshall stability was decreased.

The goal of this research is to find a way to use waste materials, such as plastic/PET bottles, on a large scale, such as in highway construction, while remain environmentally friendly. In the first part of the analysis, basic tests such as penetration, ductility, softening point test, viscosity test, and flash & fire point tests were used to determine the stabilization of bitumen containing PET waste in shredded form. The optimal PET waste percentages for further research into bituminous concrete mixes, such as SDBC, DBM, and BM were selected based on the performance of the adjusted bitumen. Marshall values, which are determined from the Marshall stability test and include Marshall flow value (F), voids in mineral aggregates (VMA), air voids (VV), Marshall stability value (S), and voids filled with bitumen (VFB), serve as benchmark values for determining the consistency of bituminous concrete. The consistency and percentage of binder used determine the design and efficiency of bituminous concrete. The suitability of these mixes for use on the road was checked in the lab.

Methods/experimental

Aim of the study

The aim of this research is to stabilize post-consumer and industrial PET waste by combining it with bitumen, which may then be used for highway engineering projects. Numerous researchers have attempted to stabilize PET waste acquired from various sources in the past. However, comprehensive research into the performance of PET waste modified bitumen when used in bituminous mix design are urgently needed in our nation. The amount of PET trash created, collection and retrieval methods, and recovery and recycling procedures were all gathered and evaluated.

Materials and design

Waste polyethylene terephthalate (PET)

PET waste products are produced in large quantities all over the world these days. Since PET is not biodegradable, this waste poses a serious environmental threat [36]. Waste landfills, open burning, and recycling are all options for disposing of PET waste and polymers today. These methods, on the other hand, are ineffective in terms of environmental conservation. The waste landfill is the world's easiest and oldest waste disposal method, but it has resulted in a slew of problems, including land occupancy, groundwater contamination, hazardous disposal, and resource waste. As a result, it appears that reprocessing (recycling) these plastic products is the best choice. For reusing PET waste, recycling is a compelling and rational technique. Nonetheless, due to its high cost, recycling is essentially limited [37]. Figure 1 depicts the total amount of produced and discarded plastic waste from 1950 to 2015, as well as the amount predicted by 2050. Up until 2015, about 9% of this amount had been recycled. By 2050, up to 26% of waste plastic is expected to be recycled. Even if this prediction proves to be right, the amount of unrecycled plastic waste will be significant [1]. There are three distinct environmental benefits to using PET in new pavement construction, as shown in Fig. 2. The discarded PET bottles were collected after appropriate identification. The PET bottles were stripped of their caps and labels, followed by appropriate washing and drying, to remove any potential contaminants. The bottles were then broken into small pieces up to 5 cm in length and dried at 80 °C for 4 h.

Bitumen

The bitumen utilized in this investigation was provided by the Public Works Department of Aligarh (Uttar Pradesh), India. Bitumen was a grade of 60/70 penetration and was used extensively in paving. It is used in current work as a binder.

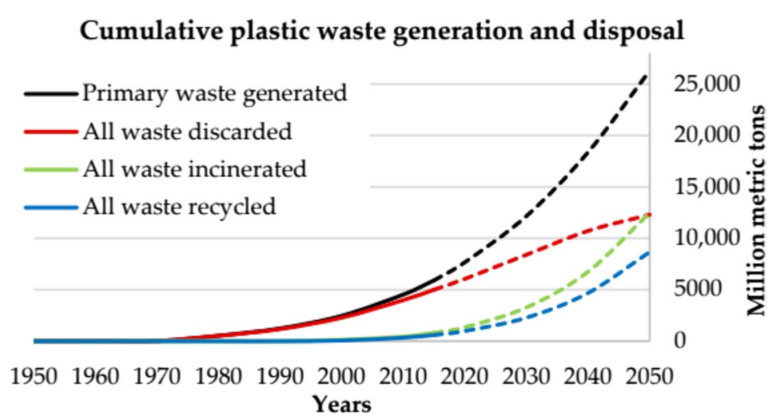

Fig. 1 The total amount of plastic waste produced and disposed from 1950 to 2015, as well as the amount predicted by 2050 [1]

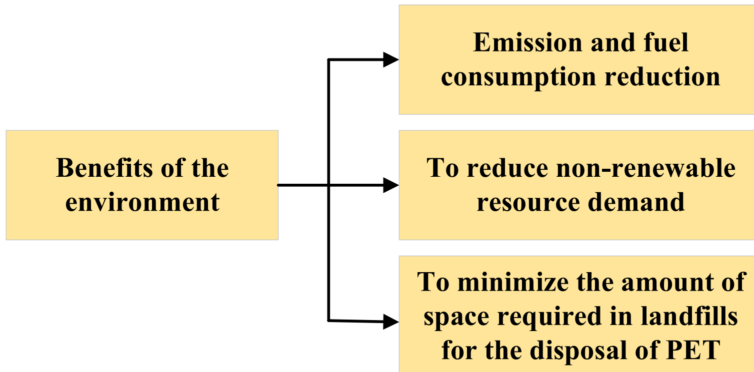

Fig. 2 Environmental advantages of using PET in the design of new pavements

Table 1 Properties of aggregates used in the present study

Aggregate tests	Tests results obtained	Requirement as per Table 500–14 of MORTH (V revision) specification (Indian Roads Congress (IRC) 2016)
Crushing value (%)	24.8	-
Impact value (%)	22	Max 24%
Los Angeles abrasion value (%)	33	Max 30%
Combined Index (%)	26	Max 30%
Water absorption (%)	0.38	Max 2%
Specific gravity of coarse aggregates	2.71	2.5–3.0
Specific gravity of fine aggregates	2.76	
Specific gravity of filler	2.63	

Aggregate

Aggregate is the primary material used in pavement construction and makes up the majority of the pavement structure. Aggregates must mainly bear load stresses that exist on roads and runways, as well as due to traffic abrasion, the material must be able to repel water. Pavements are constructed with aggregates, including cement concrete, bituminous concrete, and other bituminous structures, as well as a granular base course under the superior pavement layers. The aggregates used in this research are quartzite aggregates with a maximum size of 22.4 mm and Table 1 shows the properties of aggregates.

Mixing methods

Plastic can be blended with asphalt mixtures in two ways: dry and wet. As shown in Fig. 3, the dry process involves adding the PET after introducing and integrating the asphalt binder with the aggregate in the final section of the mixing process. In the meantime, the wet phase mixes the PET material with the asphalt binder. The heated aggregates are then coated with a "plastic-modified asphalt binder", as shown in Fig. 4. However, studies have shown that using the wet method to incorporate PET as an additive into asphalt mixtures is not feasible since PET has a melting point of about 250 °C, making maintaining a homogeneous mixture difficult. The asphalt binder can also separate from the mixture [38]. On the contrary, this process was used to perform an analysis. Due to the fine PET particles that are easy to mix with asphalt binder, the results showed that micronized PET mixtures could increase the mechanical efficiency of

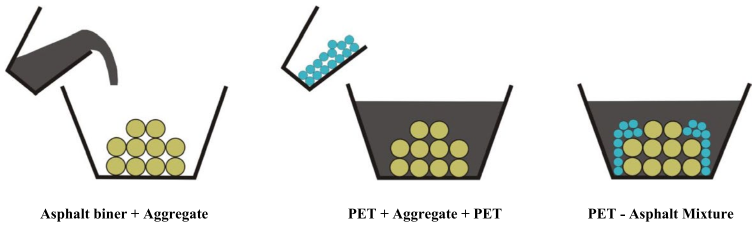

Fig. 3 Dry process

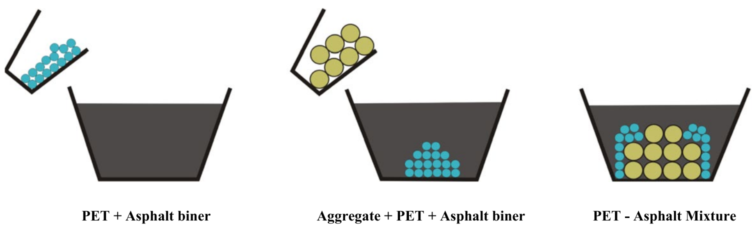

Fig. 4 Wet process

asphalt mixtures when compared to traditional ones [39]. Prior to use, the modifier must be fully mixed with the base binder. The mixing equipment used must be appropriate for the modifier type. In this analysis, the dry mix method was used. The bitumen in a jar is first heated until it becomes liquid. Seven pans were filled with hot bitumen, each with an 800 ml capacity. Each pan had a net volume of 700 gm of bitumen. Bitumen will have to be heated to about 160° C before being mixed with PET waste in pans. Bitumen pans were heated for 10–15 min to achieve this. Then, in percentages of 2%, 4%, 6%, 8%, 10%, and 12% PET waste was applied to the pans and manually mixed for about 2 min.

Experimental methodology

The following method was used to prepare the sample. In an iron pan, the necessary quantities of coarse aggregate, fine aggregate, and mineral fillers were placed. The aggregates and filler are combined and heated to temperatures ranging from 175 to 190 ℃. This is due to the fact that the aggregate and bitumen must be combined in a heated state, possibly requiring preheating. Prior to blending, the bitumen was also heated to its melting point. Weighed and stored in a separate container was the appropriate volume of shredded PET waste. The aggregates in the pan were heated for a few minutes on an operated gas stove at the above temperature. The PET waste was mixed in with the aggregate for 2 min. The requisite amount of first trial percentage bitumen is now applied to the heated aggregates, and the entire mixture is uniformly and homogeneously stirred. The mixture was adequately blended after another 10–15 min, as seen by the consistent color. For 80/100 grade bitumen, the mixing temperature might be about 154 ℃, and for 60/70 grade bitumen, it may be around 160 ℃. The mixture was then poured into a casting mold, yielding a compacted bituminous mix specimen with a thickness of 63.5±3 mm. The Marshall hammer was then used to compress the mix. The samples with molds were then held separate and labeled. In the next experiment, increase the bitumen content by 0.5% and repeat the process. Figure 5 depicts the prepared samples.

Results and discussion

Effect of plain bitumen on Marshall design

Figures 6, 7, 8, 9, 10, and 11 display the relationships between the bitumen content and the design values of the SDBC mix, which range from 3.5 to 6.0% with a 0.5% interval. The value of Gm and S increases as the bitumen content rises up to 5%, and then, both properties decrease. VV decreases as bitumen content increases. As the bitumen content increases, the value of F, VFB, and VMA all increases.

DBM mix design values for different bitumen content ranging from 3.5 to 6.0% with a 0.5% interval. The plots in Figs. 6, 7, 8, 9, 10, and 11 can be studied the S and Gm increase as the bitumen content rises up to 4.5%, and then, both properties decrease. VV decreases as bitumen content increases. As the bitumen content increases, the value of F, VMA, and VFB all increases.

BM mix design values corresponding to various bitumen content ranging from 3.0 to 5.0% with a 0.5% interval. The curves in Figs. 6, 7, 8, 9, 10, and 11 can be used to study the mix's design values. The value of S and Gm increases as the bitumen content rises up to 3.5%, and then, both properties decrease, whereas VV decreases as bitumen content increases, also F, VMA, and VFB.

Calculations for optimum bitumen content for SDBC, DBM, and BM

The amount of bitumen content with the highest Marshall stability value and lowest Marshall flow value is known as optimum bitumen content. To calculate the optimum bitumen content, six graphs are plotted with binder content values against Gm, F, S, VV, VFB, and VMA. The graphs can be used to calculate the average value of the three binder contents. Bitumen content according to MoRTH's specification of 3.5%, 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% is used to find out what the best bitumen content is for SDBC and DBM mixture, and 3.0%, 3.5%, 4.0%, 4.5%, and 5.0% is used to identify the optimum bitumen content for BM mixture Indian Roads Congress [40]. Figures 6, 7, 8, 9, 10, and 11 depict the Marshall test results for SDBC, DBM, and BM mix design mixed with plain bitumen. Therefore, the optimum bitumen content (B_0) for SDBC and DBM mix design is found to be 4.87% and 4.44%, respectively, whereas for the B_0 for BM mix design found to be 3.543%.

Effect of PET on plain bitumen

Effect of PET on penetration of bitumen

The most common control test for penetration grade bitumen is penetration. The penetration is a measurement of the consistency or hardness of bitumen. The effect and variation in penetration value with different bitumen and PET percentages is shown in the Figs. 12 and 13, respectively, which indicates that consistency decreases as PET is added. The penetration values for the modified binders decrease as the PET content in the mix increases. When compared to the initial bitumen, the decreases are 2.55%, 4.20%, 8.11%, 10.81%, 13.96%, and 14.56%, respectively, due to the addition of 2%, 4%, 6%, 8%, 10%, and 12% of PET. PET improves the consistency and strength of the modified bitumen, so it is a good thing. In one way, this is beneficial because it may help the mix avoid rutting.

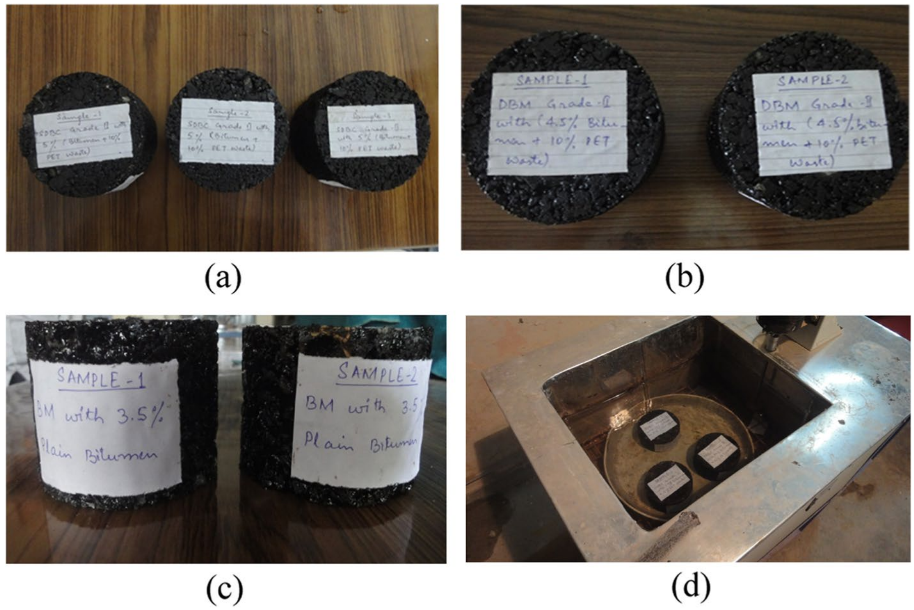

Fig. 5 Different Marshall samples. **a** Marshall samples for SDBC. **b** Marshall samples for DBM. **c** Marshall samples for Bituminous Macadam. **d** Marshall samples in thermostatically controlled water bath

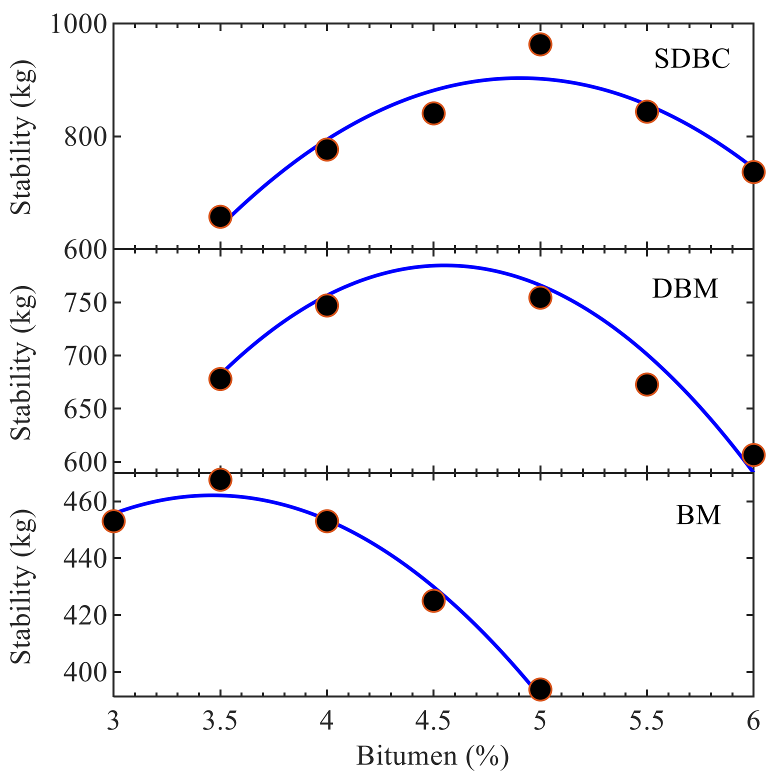

Fig. 6 Relations between Marshall stability with bitumen content for SDBC, DBM, and BM

Effect of PET on ductility of bitumen

The binders must form ductile thin films around the aggregates, which improves the aggregates' physical interlocking. The binder material would break if it lacked adequate ductility, exposing the previous pavement surface. This, in fact, has a negative impact on

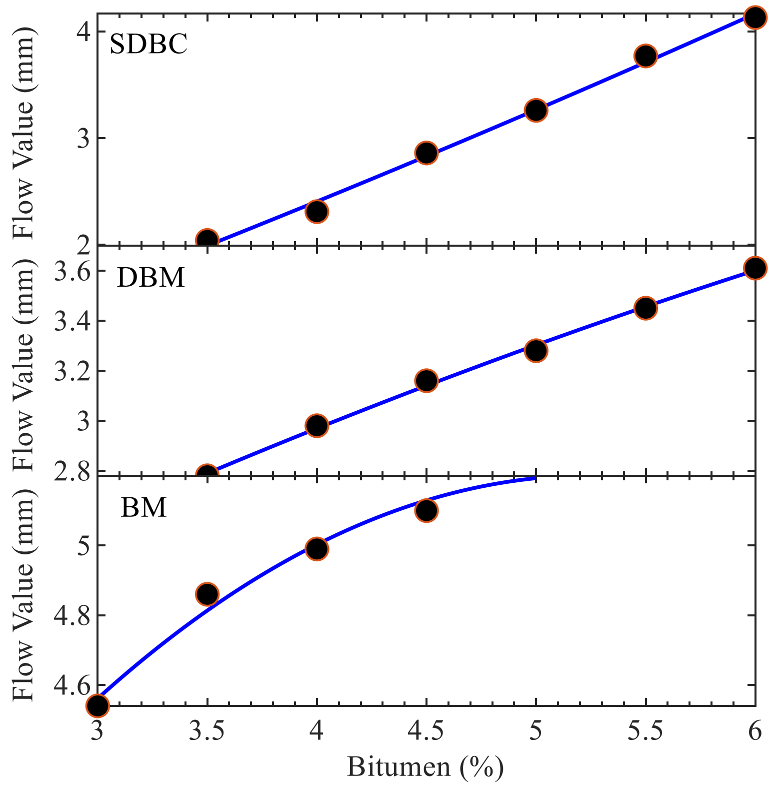

Fig. 7 Relations between flow value with bitumen content for SDBC, DBM, and BM

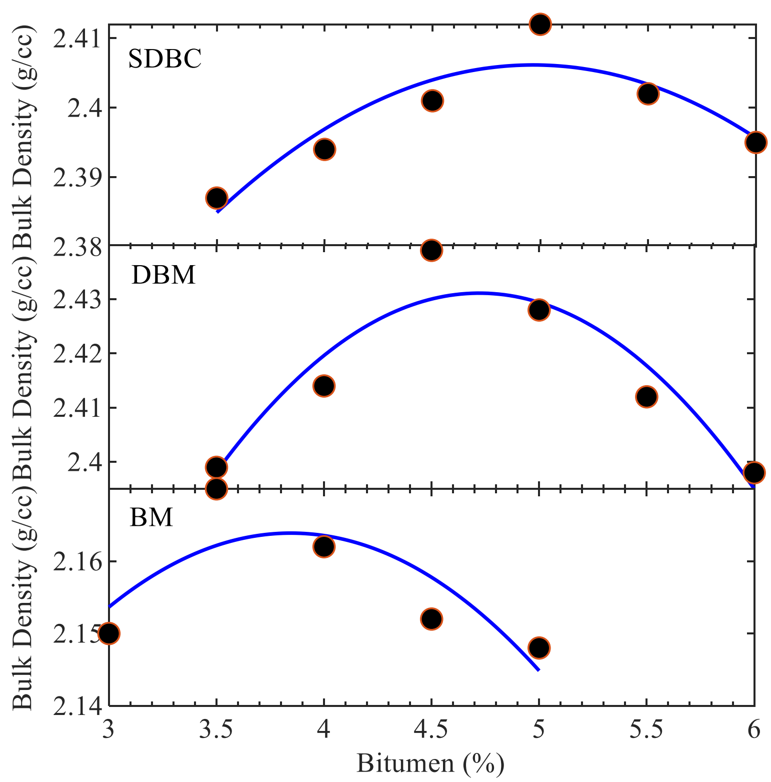

Fig. 8 Relations between bulk density with bitumen content for SDBC, DBM, and BM

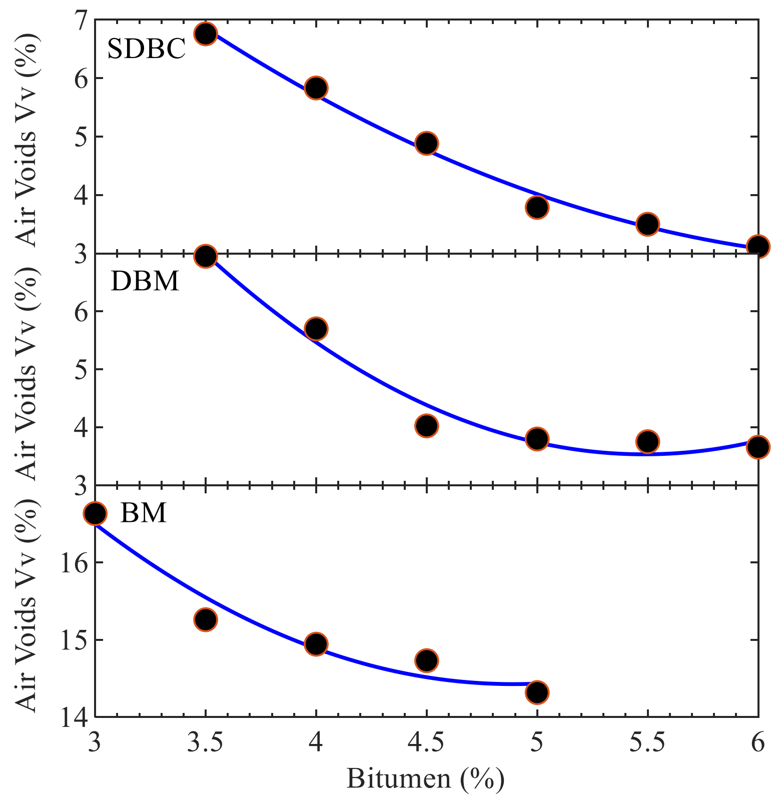

Fig. 9 Relations between air voids with bitumen content for SDBC, DBM, and BM

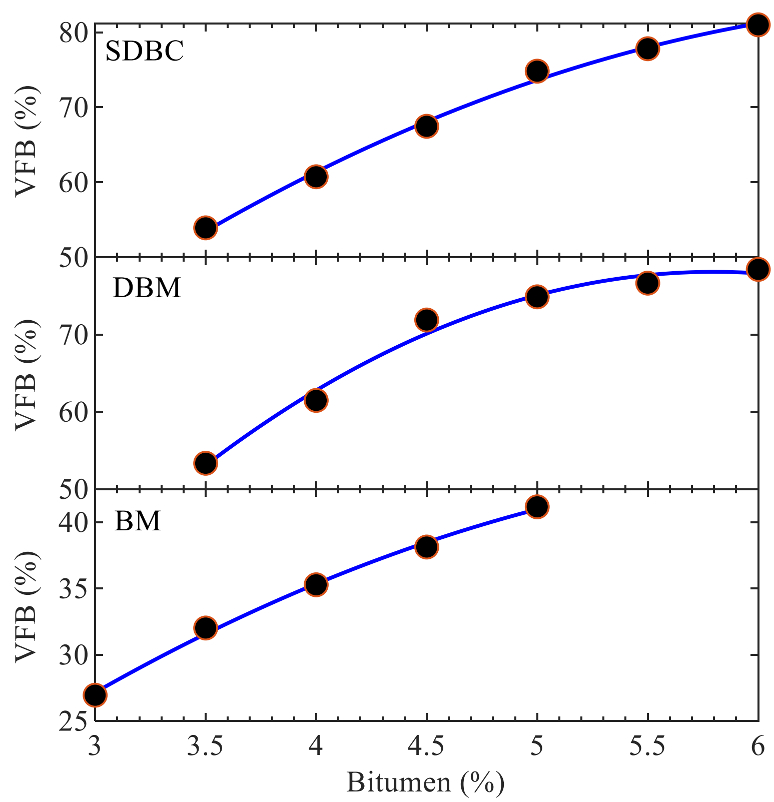

Fig. 10 Relations between voids filled with bitumen with bitumen content for SDBC, DBM, and BM

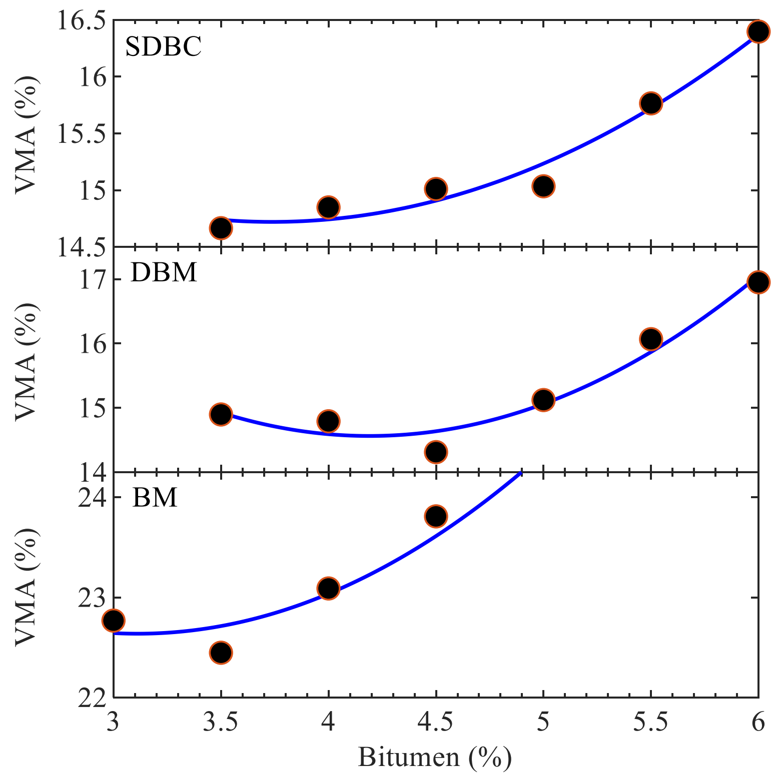

Fig. 11 Relations between voids in mineral aggregates with bitumen content for SDBC, DBM, and BM

the pavement structure. As a result, it can be concluded that ductility should not be too high, as this will cause the pavement structure to stretch and take a non-uniform shape, which is highly undesirable, nor should it be too low, as this will cause cracks. A bitumen binder must have a certain level of ductility. The effect of ductility value with different percentages of bitumen changed PET is shown in.

Figure 14, and it indicates that ductility decreases as PET is added. If the PET content in the mix increases, the ductility of the modified binders decreases. As PET amounts range from 2 to 12%, the ductility of plain bitumen decreases by 3.06%, 7.14%, 10.20%, 16.33%, 19.39%, and 24.49%, respectively, as shown in Fig. 15. This decrease in ductility is due to polymer molecules interlocking with bitumen. The measured values are within the Indian standard's permitted limitations.

Effect of PET on softening point of bitumen

The softening point increases as the PET content increases as seen in the Figs. 16 and 17. The study findings show that adding PET to bitumen improves the softening point value and improves the softening point in tandem with the PET material. This means that the binder's resistance to the effects of heat has improved, and it will have less of a propensity to soften in hot weather. The changed binder would be less vulnerable to temperature fluctuations as a result of the addition of PET. As a result of the increased softening point, it is anticipated that using PET in the bituminous mix would reduce rutting.

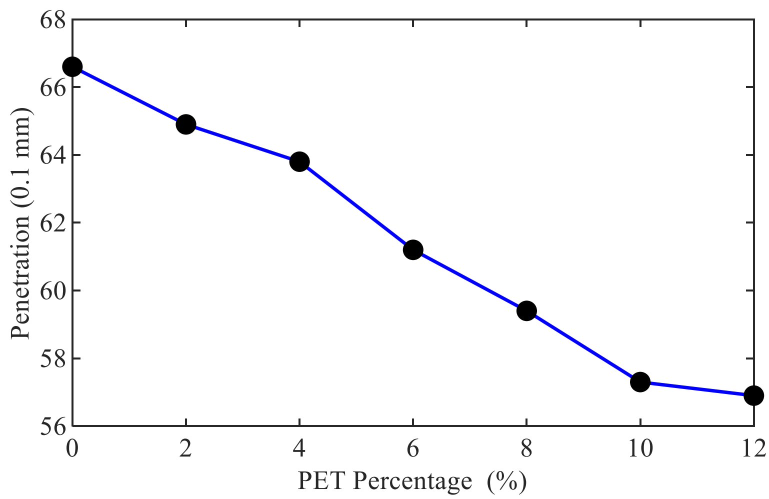

Fig. 12 Effect of PET on penetration value of bitumen

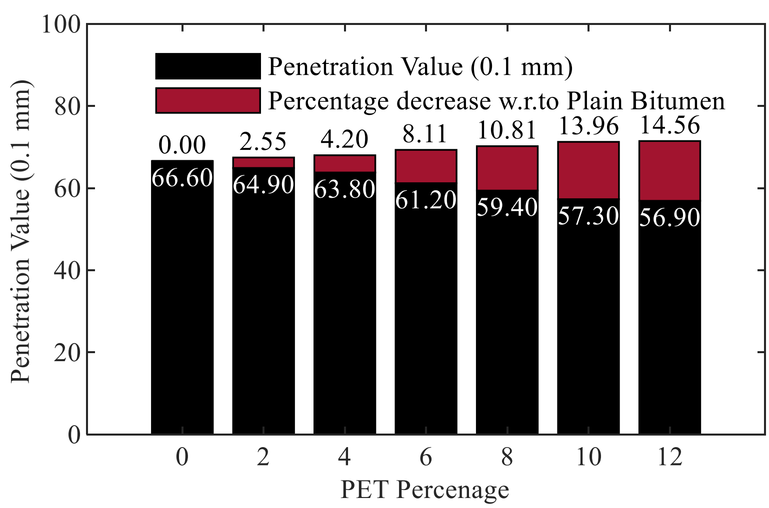

Fig. 13 Variation of penetration value with PET content

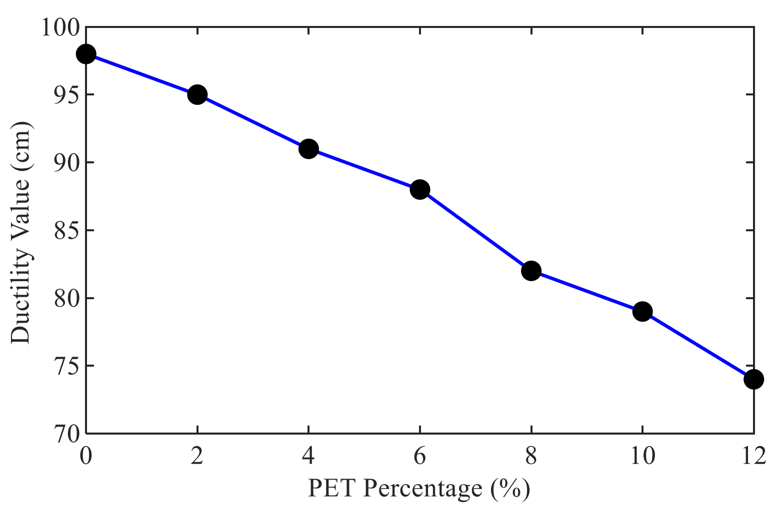

Fig. 14 Effect of PET on ductility value of bitumen

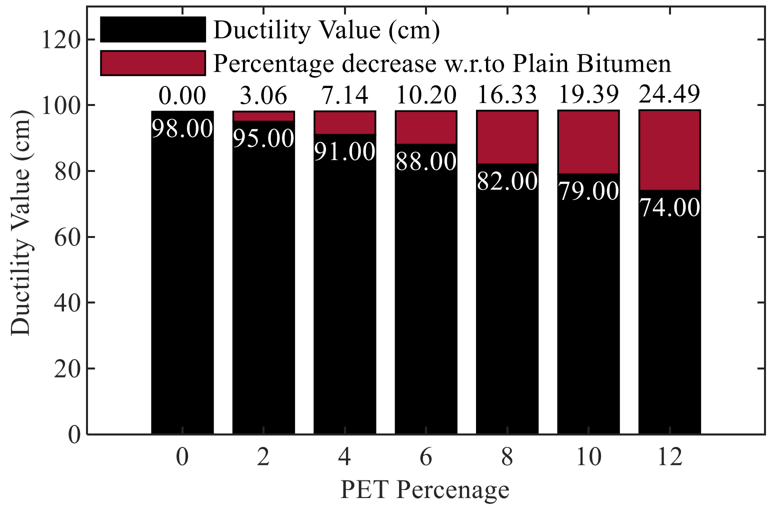

Fig. 15 Variation of ductility value with PET content

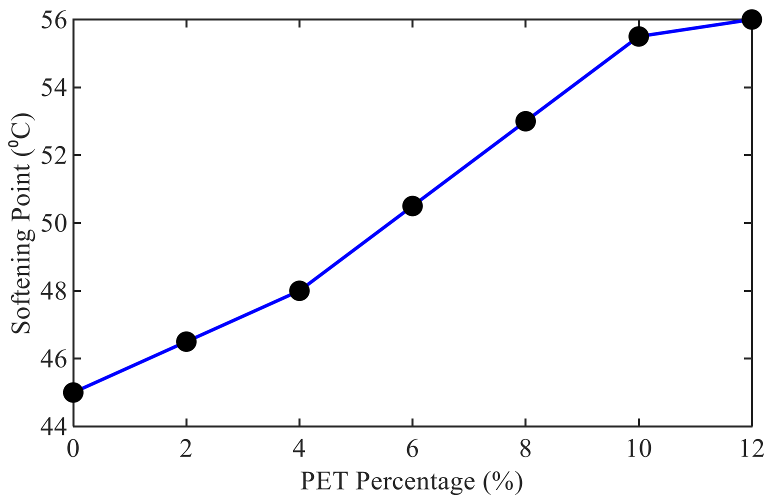

Fig. 16 Effect of PET on softening point of bitumen

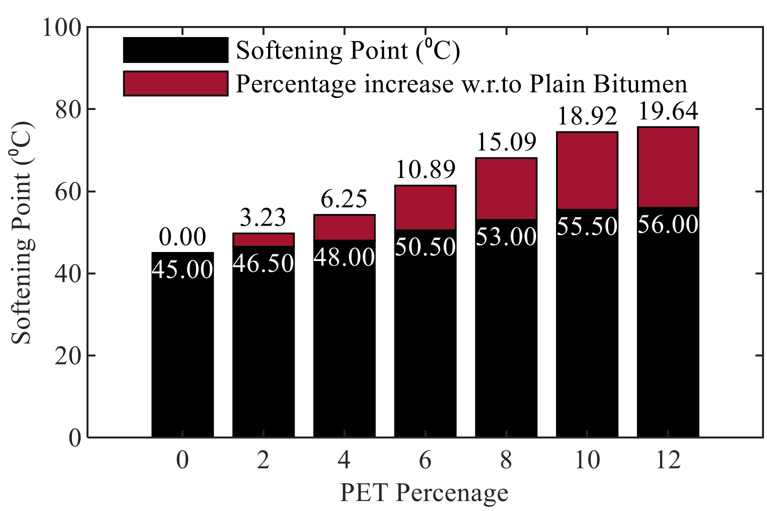

Fig. 17 Variation of softening point with PET content

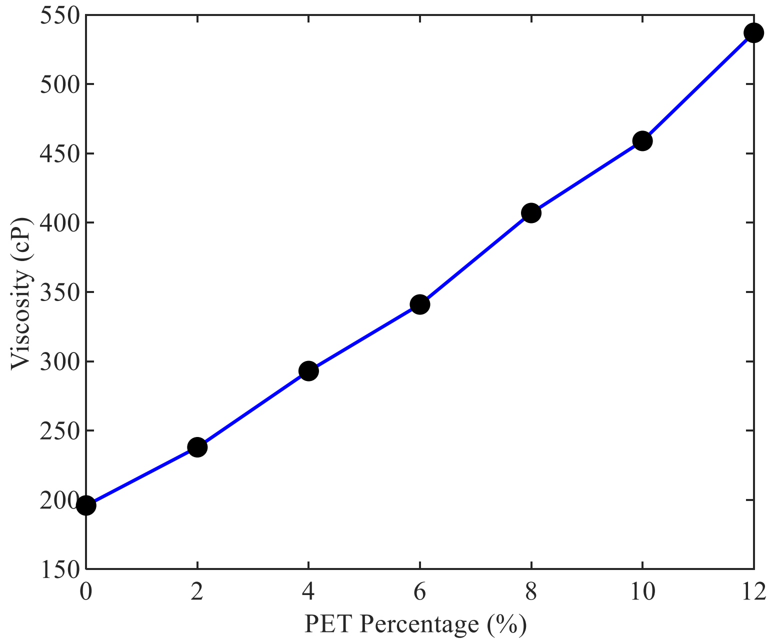

Fig.18 Effect of PET on viscosity of bitumen

Effect of PET on viscosity of bitumen

The viscosity test was conducted at the specified temperatures to determine the viscosity change of PET-modified binders, as seen in Figs. 18 and 19. The maximum viscosity value at 135 °C must be less than 2000 cP, according to the standards. The introduction of PET enhanced the viscosity of the virgin binder, indicating that all binders satisfied the criteria. Virgin binder had a viscosity of roughly 196 cP at 150 °C, whereas 10% and 12% PET had viscosities of around 459 cP and 537 cP,

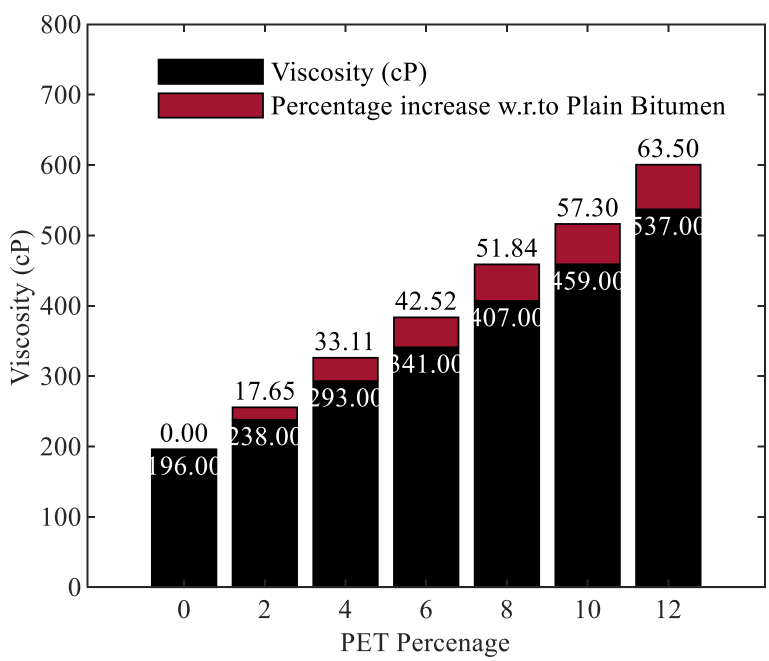

Fig. 19 Variation of viscosity with PET content

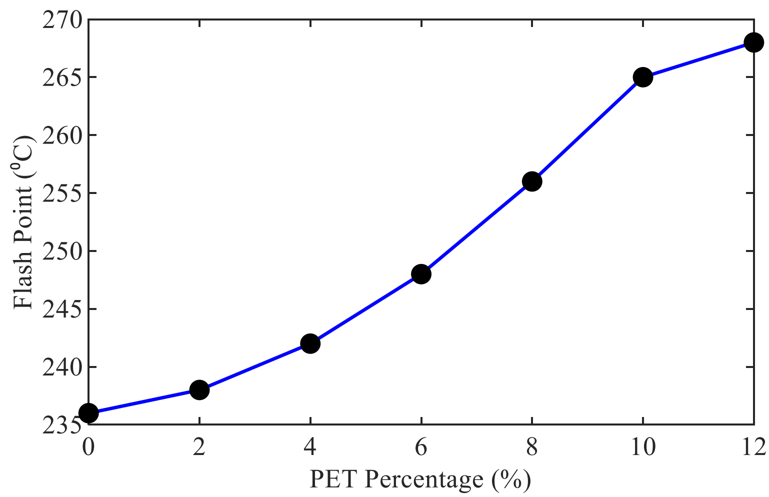

Fig. 20 Effect of PET on flash point of bitumen

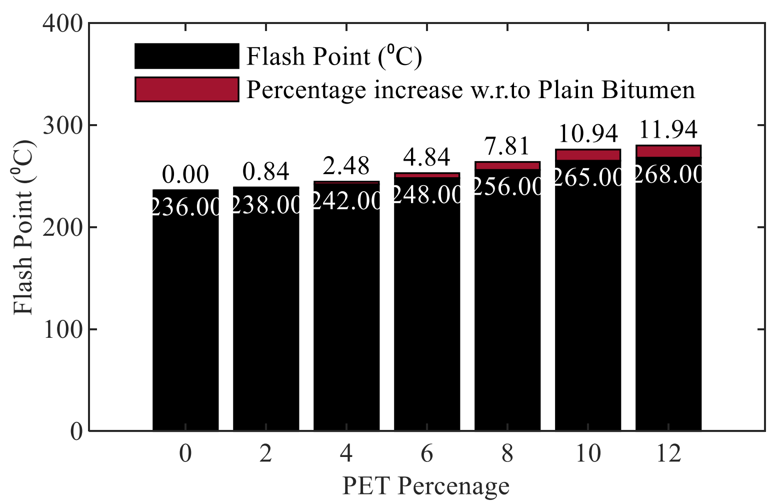

Fig. 21 Variation of flash point with PET content

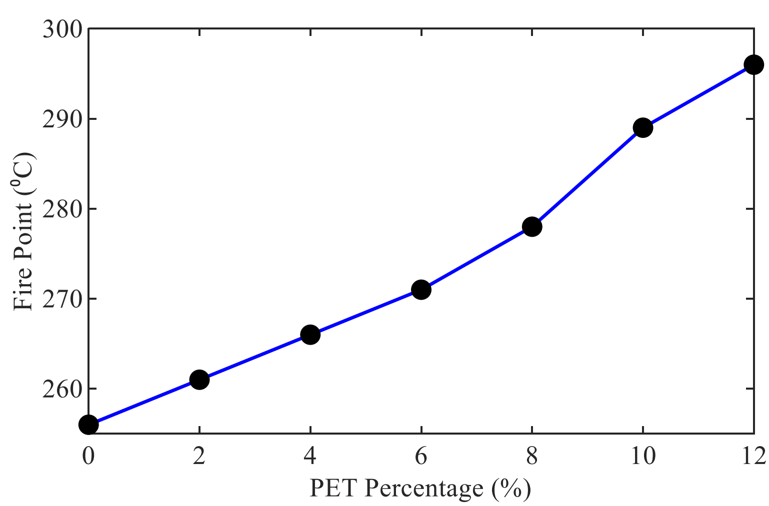

Fig. 22 Effect of PET on fire point of bitumen

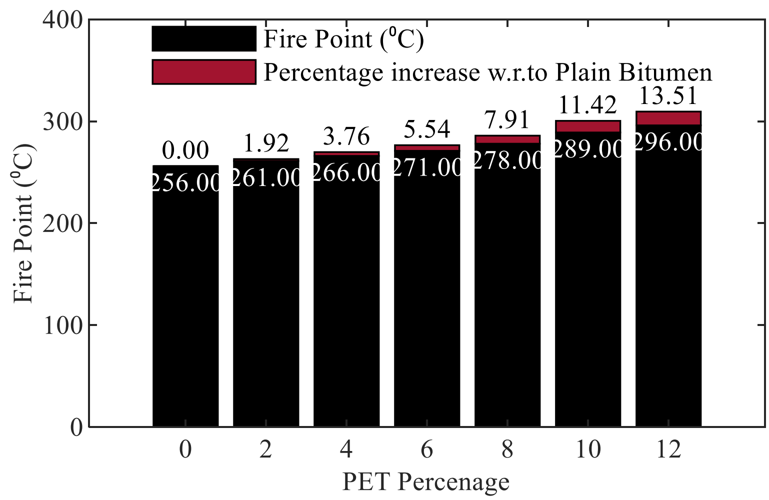

Fig. 23 Variation of fire point with PET content

Table 2 Job mix for 25 mm SDBC (grade II)

Materials used	Quantity (%)	Specific gravity
Aggregates (11.2 mm)	30	2.7
Aggregates (5.6 mm)	48	2.74
Fillers (stone dust)	22	2.63
Binder (bitumen)	5	1.021

Table 3 Job mix for 25 mm DBM (grade II)

Materials used	Quantity (%)	Specific gravity
Aggregates (25–10 mm)	30	2.676
Aggregates (10–5 mm)	28	2.732
Aggregates (5 mm)	40	2.76
Fillers (stone dust)	2	2.63
Binder (bitumen)	4.5	1.021

Table 4 Job mix for 50 mm BM

Materials used	Quantity (%)	Specific gravity
Aggregates (22.4 mm)	32	2.68
Aggregates (11.2 mm)	38	2.7
Aggregates (5.6 mm)	28	2.74
Fillers (stone dust)	2	2.63
Binder (bitumen)	3.5	1.021

respectively. It has been discovered that adding PET to plain bitumen increases its viscosity. When PET is added at a rate of up to 12%, the viscosity value increases significantly. As a result, PET modified bitumen have greater workability than plain bitumen.

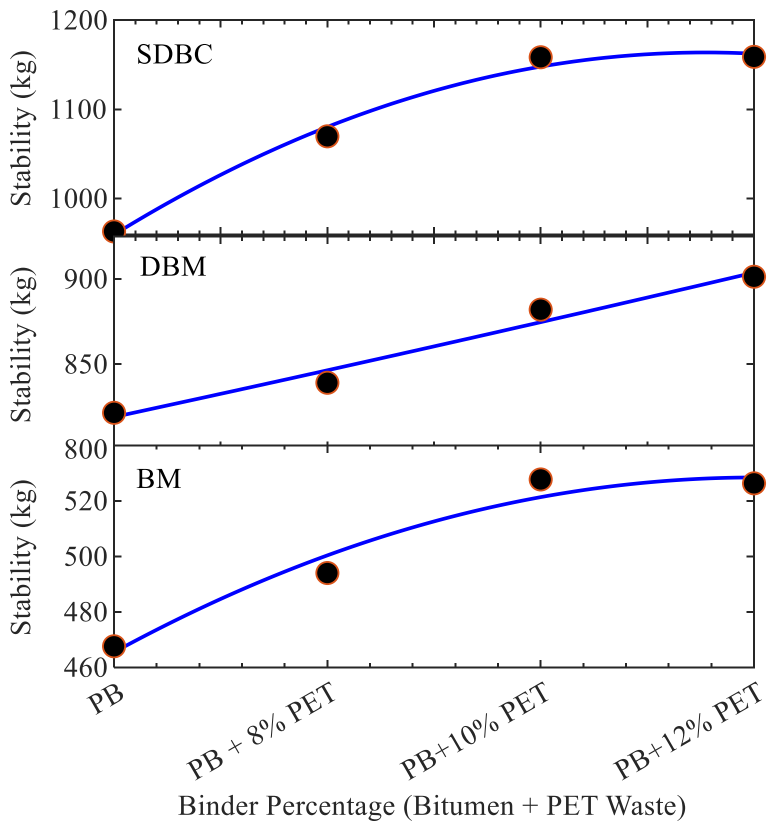

Fig. 24 Relations between Marshall stability and binder content for modified SDBC, DBM, and BM

Effect of PET on flash & fire point of bitumen

The flash and fire points of the PET waste bitumen blend have been studied to better grasp the blend's inflammability. Plain bitumen has a flash and fire point of 230–250℃. The inflammability of the blend increases as the percentage of PET increases so it becomes more resistant to heat as shown in Figs. 20, 21, 22, and 23, according to the experimental results. The mixture has improved its resistance to fire. It reduces the chances of catching fire during the melting and mixing of bitumen, as well as during the service life of the pavements.

Job mix formula (Marshall stability test results)

Different combinations of bitumen and PET were used to create job mix formulae for various bituminous constructions such as SDBC, DBM, and BM as shown in Tables 2, 3 and 4. The Marshall stability test results were used for the B0 in the conventional sample and the plastic bottle content modified sample.

Effect of PET on nodified Marshall design

Marshall stability, in particular, is frequently recognized as a critical feature in asphalt mixture design, and it refers to a mixture's ability to resist deformation caused by applied loads. As a result of the graphs, the design values of the mix

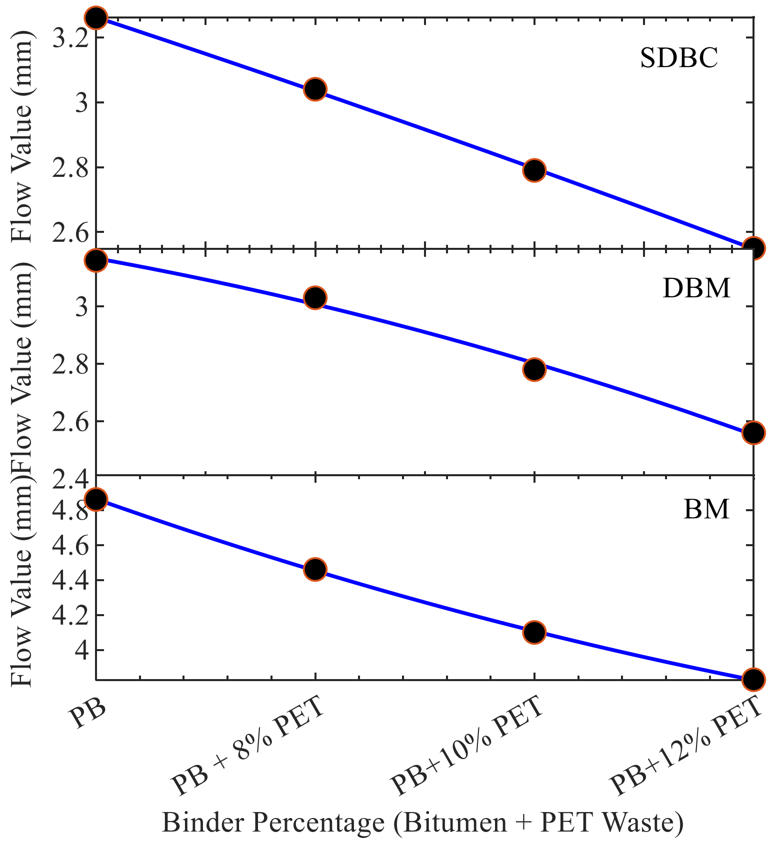

Fig. 25 Relations between Marshall flow value and binder content for modified SDBC, DBM, and BM

corresponding to the optimum PET content are observed and summarized. The Marshall stability of the mix has increased noticeably, and other properties have improved as well. The addition of PET to plain bitumen improves the various stability parameters for SDBC, such as Marshall stability value, Marshall flow value, bulk density, air voids, VMA, and VFB, as shown in Figs. 24, 25, 26, 27, 28, and 29. As a result, the graphs reveal the mix design values that correspond to the optimum PET material which concludes that the properties of the PET-enhanced mix are much superior to those of the non-PET-enhanced mix. The numerous stability parameters for DBM, such as Marshall stability value, Marshall flow value, bulk density, air voids, VMA, and VFB, improve dramatically when PET is added to plain bitumen, as shown in Figs. 24, 25, 26, 27, 28, and 29. We can conclude that the mix's stability and flow values have improved significantly and that other properties have improved as well. Figures 24, 25, 26, 27, 28, and 29 that when PET is added to plain bitumen, various stability parameters for BM such as Marshall stability value, Marshall flow value, bulk density, air voids, VMA, and VFB improve significantly. According to Fig. 30, various design parameters significantly enhance the stability of SDBC, Marshall stability increases to 19.64% with the introduction of waste PET into plain bitumen, the Marshall flow value drop to 19.30% followed by air void percent and voids in mineral aggregate percent to 20.75% and 5.34%

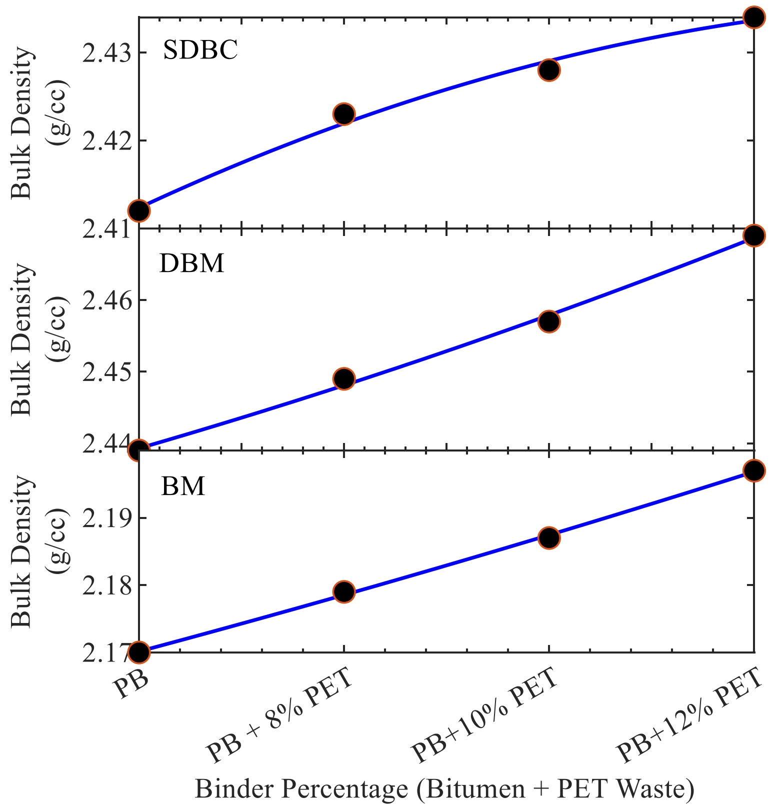

Fig. 26 Relations between bulk density and binder content for modified SDBC, DBM, and BM

correspondingly, whereas the bulk density and the percentage of voids filled with bitumen increase to 1.03% and 5.72%, respectively. Figure 31 shows the enhancement in DBM mix design experimental parameters, as waste PET is mixed into the plain bitumen, Marshall stability increases to 9.86%, Marshall flow value decreases to 18.47%. Air void percent and voids in mineral aggregate percent decrease to 24.56% and 7.61%, respectively. The bulk density and the percentage of voids filled with bitumen all rise to 1.34% and 7.05%, respectively. As shown in Fig. 32, when the PET waste is blended into the bitumen for the design of BM, Marshall stability increases to 11.52%, Marshall flow value decreases to 18.48%. Air void percent and voids in mineral aggregates percent decrease to 4.14% and 3.76%, respectively. The bulk density and the percentage of voids filled with bitumen all rise to 1.05% and 0.84%, respectively. The different stability plots of plain and modified bitumen mixtures are shown in Figs. 6, 7, 8, 9, 10, and 11 and Figs. 24, 25, 26, 27, 28, and 29. When compared to the virgin binder mixtures, the mixtures made with 10% PET had the maximum stability values, with an increase of 9.86 to 19.64%. The difference in polarities between the PET and aggregate enhances adhesion tendencies between the mixture, which increases stability. In the study, mixtures created with 12% PET had lower stability than mixtures prepared with 10% PET, suggesting that a 10% PET additive concentration is more suited for maintaining maximum mixture stability.

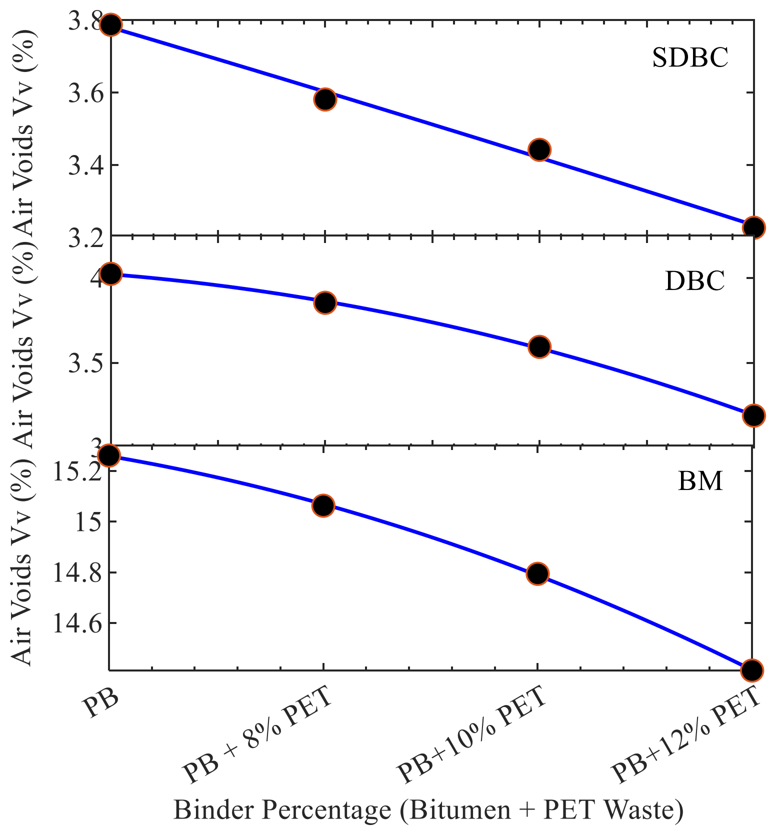

Fig. 27 Relations between air voids and binder content for modified SDBC, DBM, and BM

Stripping value test

The aggregate's stripping value was first tested with simple bitumen. The waste PET was then mixed with bitumen in percentages of 8%, 10%, and 12%. After that, the blend was applied to the aggregates, and the samples were immersed in water to be examined. Even after 48 h, it was found that adding 12% PET waste results in zero percent stripping as shown in Table 5. This indicates that the mix is more water-resistant. This is due to the PET waste changed bitumen's superior binding properties.

Microstructural analysis of bitumen/modified bitumen using scanning electron microscope (SEM)

Morphology of several of the selected samples was studied using scanning electron microphotography (SEM). A JEOL JSM-6510 W with a LaB6 filament was used for the SEM at the University Sophisticated Instrumentation Facility in AMU, Aligarh. Scanning electron micrographs SEM of bitumen are shown in the Fig. 33 (a). The.

micrographic observation of bitumen reveals the existence of surface cracks, which may be one of the reasons for the pavement's failure. The SEM micrograph of bitumen + 8% PET is shown in the Fig. 33 (b). The load bearing strength of the bitumen pavement strengthened with different percentages of PET increased as the bulk density of the mix increased. The SEM micrograph of bitumen + 10% PET is shown in the

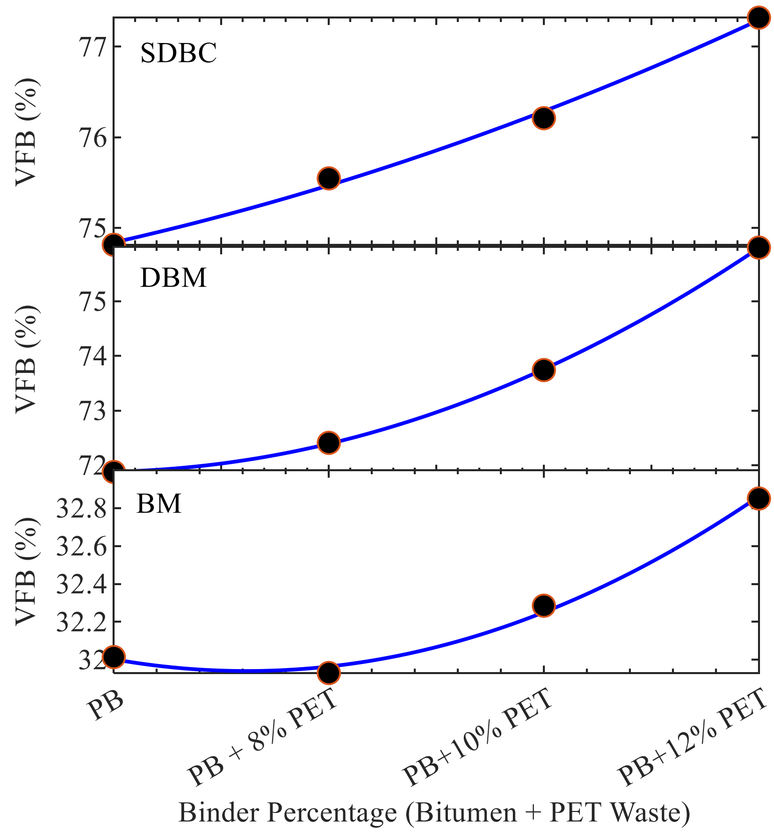

Fig. 28 Relations between voids filled with bitumen and binder content for modified SDBC, DBM, and BM

Fig. 33 (c). The micrographic analysis of bitumen with 10% PET reveals an excess of spherical, sub-rounded, and irregular particles. Furthermore, the addition of 10% PET to bitumen improves the mix's consistency, with all design values falling within acceptable limits. The SEM micrograph of bitumen with 12% PET is shown in the Fig. 33 (d). The inclusion of 12% PET improves design parameters, but there is no difference between the design parameters of these two mixes as compared to the bituminous mix of 10% PET.

Conclusions

The following conclusions and recommendations have been obtained as a result of this research.

- Since the waste materials were totally recycled with no negative effects on the environment, the current stabilization process is very successful in controlling environmental pollution. This research also promotes the widespread use of PET waste in highway engineering applications.
- The study's findings revealed that the modified mixture performed better than the non-modified mixtures. A stronger binding between binder and aggregates was obtained by adding PET to the bitumen. Marshall stability values increase as PET content increases indicating that the modified mix is durable and long-lasting.

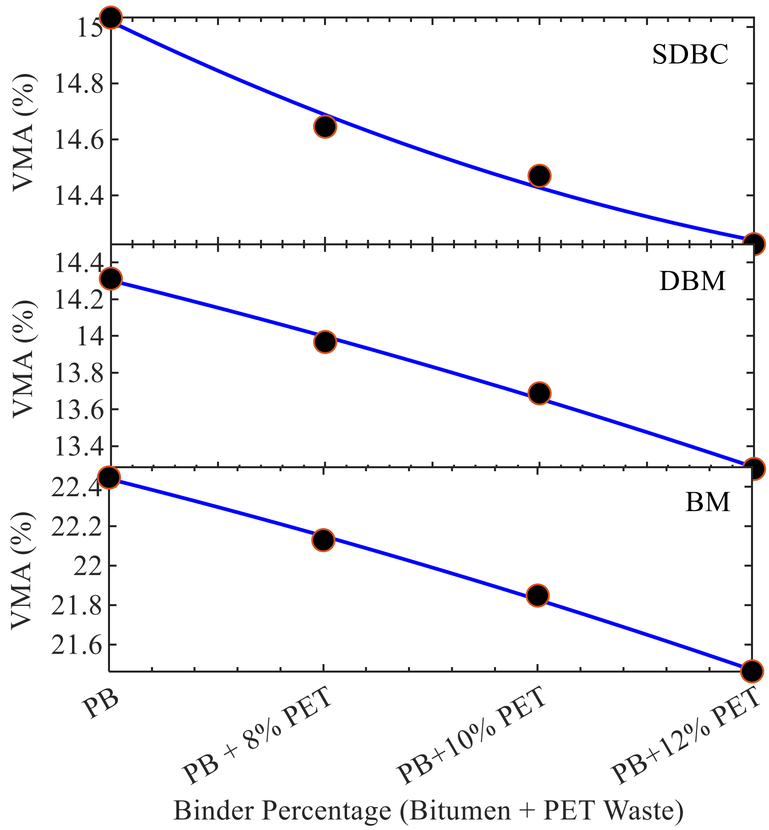

Fig. 29 Relations between voids in mineral aggregates and binder content for modified SDBC, DBM, and BM

- It has also been discovered that the maximum amount of PET waste that can be applied to Bitumen is up to 12%. When PET waste is added in amounts greater than 12%, PET particles are separated.
- In this experiment, 60/70 penetration grade bitumen was adjusted with different percentages of PET in small pieces of 3 to 5 cm ranging from 2 to 12%. According

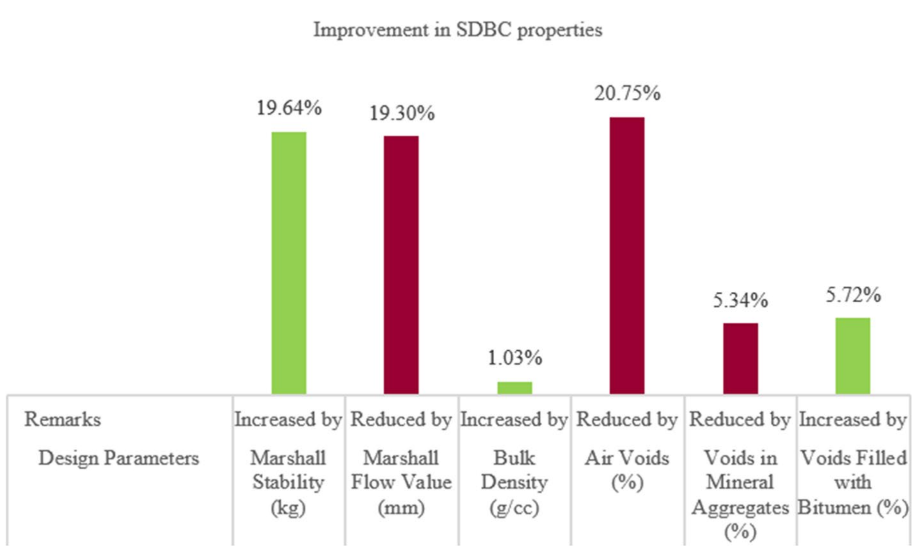

Fig. 30 Enhancement in the properties of modified SDBC

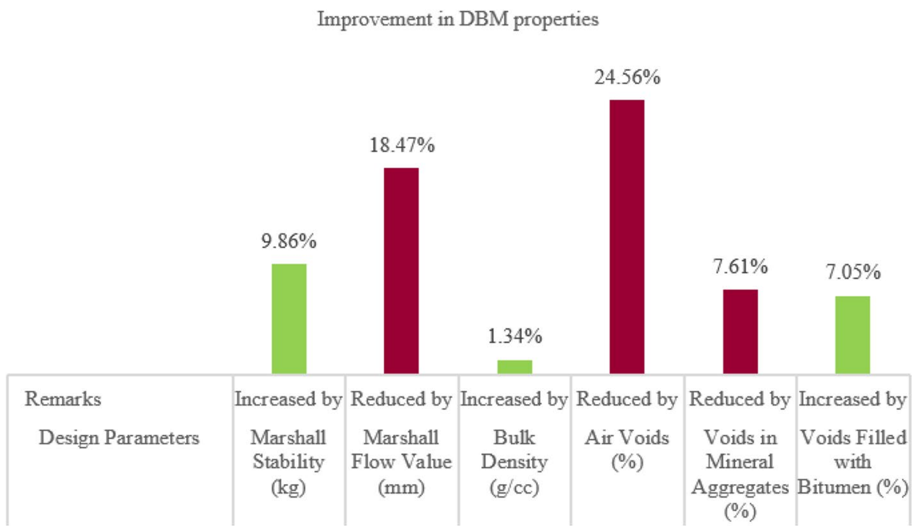

Fig. 31 Enhancement in the properties of modified DBM

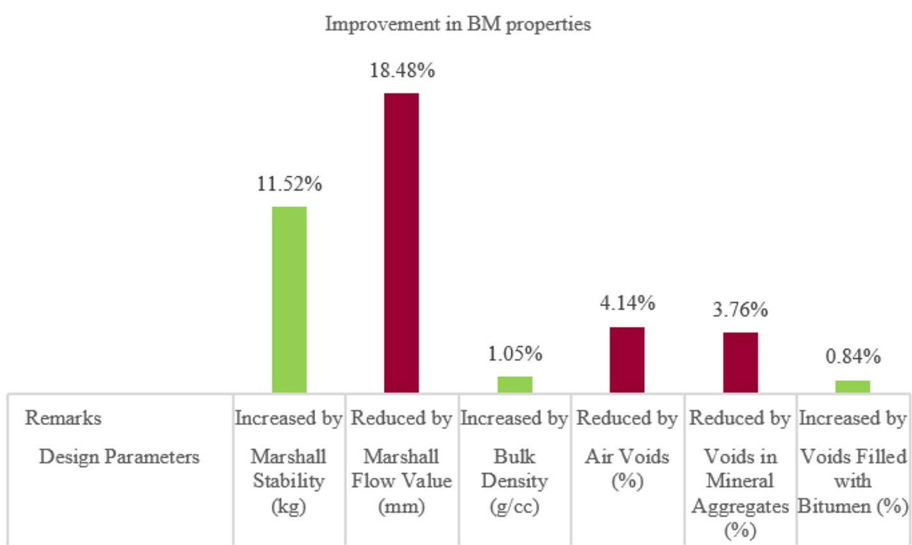

Fig. 32 Enhancement in the properties of modified BM

Table 5 Stripping value of aggregates

Time (hours)	Stripping value at 40℃ (%)			
	Bitumen (PB)	PB + 8% PET	PB + 10% PET	PB + 12% PET
1	0	0	0	0
3	3	2	0	0
24	5	3	0	0
48	5	3	0	0

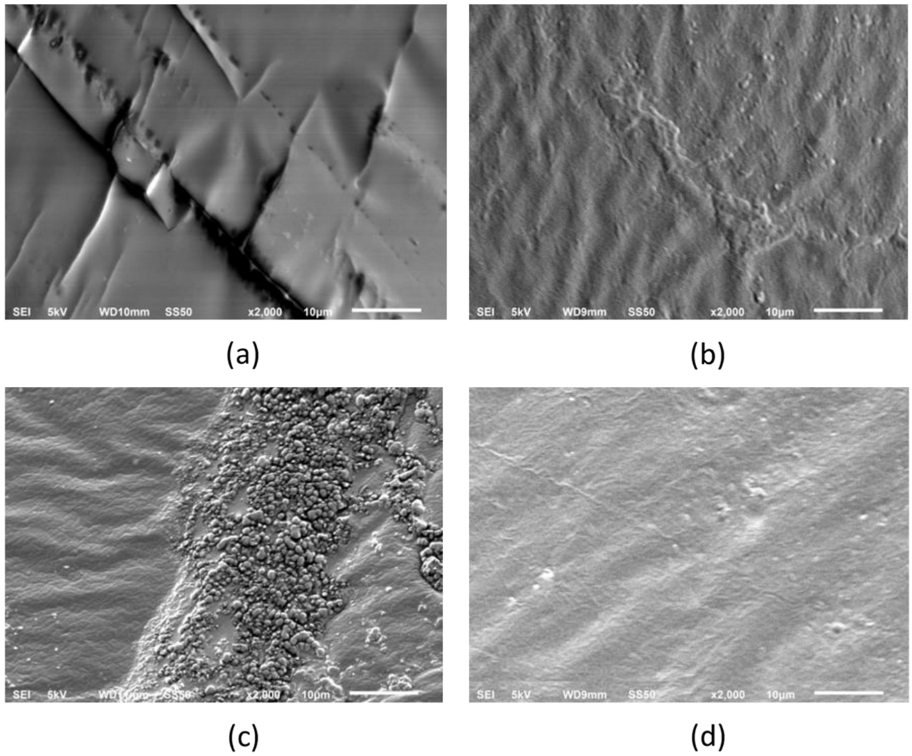

Fig. 33 Scanning electron micrograph (SEM). **a** Bitumen, **b** bitumen with 8% PET, **c** bitumen with 10% PET, and **d** bitumen with 12% PET

to the findings, the maximum percentage of PET used as a bitumen modifier was between 10 and 12% of the total binder weight.

- After analyzing the data from the Marshall test, the PET modified sample outperformed the conventional sample in terms of deformation resistance. The results clearly show that the PET modified mix has a lower rate of deformation than the traditional mix.
- PET when combined with hot bitumen, forming an oily coating over the aggregate. This demonstrates that molten PET has good binding properties. As compared to the sample with the ordinary mix, the sample with plastic bottles had a longer shelf life. Plastic's binding property extends the life of the sample while also improving the stripping value of the aggregates. As a result of this technology, road maintenance will be reduced, and the use of plastic bottles will help to reduce non-biodegradable waste.
- The presence of PET decreases air voids, which prevents entrapped air from moisture absorption and oxidizing bitumen. As a result, the Marshall stability value, stripping value, and other design parameters have improved, potentially preventing the creation of potholes.
- The impacts of the PET on asphalt mixes with various aggregates and grades of bitumen will be examined in future research with environmental and economic performance will be assessed using life cycle cost assessment and life cycle analysis, respectively.

Abbreviations

PET Polyethylene terephthalate
SDBC Semi-dense bituminous concrete
DBM Dense graded bituminous Macadam
BM Bituminous Macadam
VV Air voids in the mix
F Flow value
VFB Voids filled with bitumen
VMA Voids in mineral aggregates
Gm Bulk density of the mix
S Marshall stability value
MoRTH Ministry of Road Transport and Highways
B_0 Optimum bitumen content
SEM Scanning electron microscope

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Author's contributions

Conceptualization: Prof. MSA, methodology, formal analysis, and investigation. SAA, writing—original draft preparation and writing—review and editing. Prof. MSA, resources, Department of Civil Engineering, ZHCET, AMU. Both authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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