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Mechanical and economical feasibility of LDPE Waste-modified asphalt mixtures: pathway to sustainable road construction

Aakash Singh & Ankit Gupta

This research study evaluates the impact of low-density polyethylene (LDPE) modified asphalt binder on the mechanical performance and economical feasibility of asphalt concrete (AC) mixtures. LDPE-modified mixtures were compared with conventional mixes prepared with various binders commonly used in India, i.e., VG 30, VG 40, Polymer-Modified Binder (PMB), and Crumb Rubber Modified Binder (CRMB). LDPE-modified mixtures exhibit superior mechanical performance, increasing the stiffness of AC mixtures by 171% and 125% at 25 °C and 35 °C, respectively, compared to VG 30 base binder. Additionally, the indirect tensile strength (ITS) improved by 51% over VG 30. LDPE-modified mixtures also showed improved resistance to permanent deformation, with RT_{Index} values up to 133.46% higher than VG 30, and higher fatigue resistance, as indicated by increased CT_{Index} values compared to VG 30 and CRMB. However, the CT_{Index} values for LDPE-modified mixtures were 26.32% and 56% lower than those for VG 40 and PMB, respectively. Pavement analysis using 3D-Move showed lesser deflections at pavement layer interfaces, resulting in higher rutting and fatigue life for LDPE-modified pavements. Furthermore, LDPE-modified pavements showed up to 57% higher fatigue life (N_f) and up to 42.33% higher rutting life (N_r) than other pavements. The economic analysis showed that the cost of LDPE-modified pavements is comparable to VG 40 and around 10% more economical than pavements containing PMB. Using LDPE also offers environmental benefits by repurposing up to 750 kg for every kilometer of single-lane pavement section having 50mm thick surface course. Overall, LDPE-modified asphalt mixtures present a sustainable and high-performance solution for asphalt pavement construction.

Keywords Waste LDPE, Asphalt mixtures, Permanent deformation, Pavement design, Economic analyses, Polymer-Modified Binder (PMB), Crumb Rubber Modified Binder (CRMB)

Plastic production and use are increasing worldwide, surpassing recycling efforts. This highlights the urgent need for effective waste management strategies[1,2]. In India, plastic production ranges from 40 to 115 kg per ton of solid waste, constituting around 10% of municipal solid waste[1]. The Central Pollution Control Board reports that in 2019/20, 35 Indian states and union territories produced about 3.47 million tonnes of plastic waste. Despite efforts, only around 50% of this waste is properly disposed of and recycled, leading to significant environmental degradation.

Among the unrecycled fraction, over 70% comprises polyethylene (PE) (as shown in Fig. 1), primarily low-density polyethylene (LDPE), which holds minimal value after recycling in further supply chains[3]. This challenge isn't confined to developing countries; in the United States, only 9.1% of plastic waste was effectively recycled in 2015, with the majority ending up in landfills[4,5]. Traditional disposal methods like landfilling and incineration are found inadequate due to limited land availability, pollution, and high costs[6,7]. Recent research suggests plastic recycling offers a sustainable alternative[8,9].

Notably, incorporating waste plastics into road pavements presents environmental and economic benefits[10]. This approach also aligns with global efforts to reduce carbon emissions, potentially cutting emissions in the asphalt industry by a third[11]. The United Nations Framework Convention on Climate Change (UNFCCC) underscores the critical role of the transportation sector in modern society[12]. India's commitment to reducing

Department of Civil Engineering, Indian Institute of Technology (BHU) Varanasi, Varanasi, India. ✉email: ankit.civ@iitbhu.ac.in

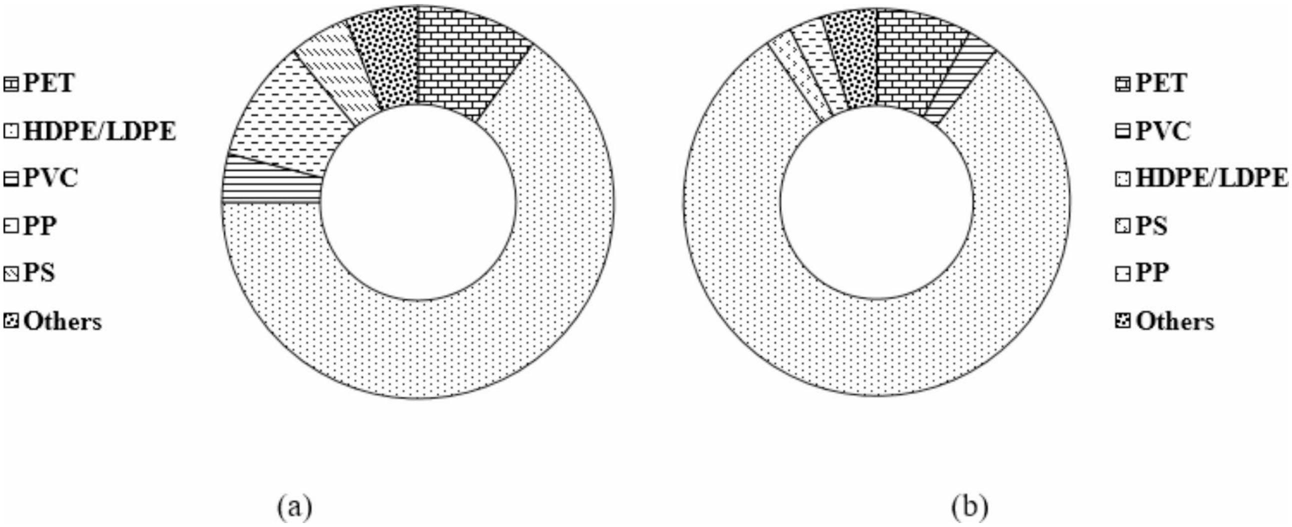


Fig. 1. Plastic waste scenario in India (**a**) generation, (**b**) non–recycled plastic waste composition.

greenhouse gas emissions emphasizes the urgency of adopting sustainable transportation solutions, including electric vehicles and durable road surfaces.

There are two different methods of adding plastics to AC pavements that are widely used. i.e., wet and dry method[13,14]. In the dry process, waste plastic is introduced either as a partial substitute for aggregates or mixed with the hot aggregates, followed by the addition of binder into the mixture[15–17]. The aggregate replacement approach is particularly suitable for rigid plastics with high melting points, such as polystyrene (PS) and polyethylene terephthalate (PET). These rigid plastics serve as either fillers or replacements for a portion of fine aggregates[16,18]. Conversely, plastics characterized by lower melting points, such as polyethylene (PE), are also used in the dry process. In the dry process, it's hypothesized that low melting temperature plastic melts, when mixed with hot aggregates, and forms a thin film enveloping the aggregates. This method is referred to as the aggregate modification, mixture modification, or binder replacement approach[19].

In contrast, the wet process involves the waste plastics being mixed with asphalt binder. The mixing was done at high shear rate and high temperature. Preference is given to the use of plastics in shredded or powdered forms, allowing for a high shear rate to achieve a homogeneous and well-dispersed amalgamation of plastics within the binder matrix[20]. As per NCHRP project 9–66 and NAPA IS: 142, the wet process is suitable for plastics having low melting temperatures[17,21]. In contrast, the dry process is universally applicable to all recycled plastics[17,22], except for PVC[17,22,23], which is subject to hazardous chlorine-based dioxin emissions[16,24,25].

Recent studies have shown significant improvements in asphalt mixture properties by using recycled plastics[14,26–28]. The possibility of using waste plastics as a binder modifier/extender shows encouraging results, especially in the mixture phase[14,29–31]. Waste plastic-modified binders improve thermal stability[32,33]and shows better rheological performance than neat binders[34–36]. Previous studies also reported that waste plastic-modified binders show higher viscosity and softening point, lower penetration value, and improved viscoelastic properties such as higher complex shear modulus and lower phase angle values[29,30,37].

When LDPE is used in asphalt concrete (AC) mixtures using the wet process, it results in reduced permanent deformation, higher resistance to moisture damage, higher stiffness, and lower susceptibility to temperature variations[19,38–40]. However, there is no consensus in the literature regarding the effects of LDPE-modified binders on fatigue resistance and low-temperature cracking performance. Some studies suggest that using lower LDPE content in binder modification improves low-temperature performance, particularly in the binder phase[41,42]. Other studies have found that AC mixes containing LDPE-modified binders show improved low-temperature performance than those prepared with unmodified base binders, even at higher LDPE content[42].

Improvements in fatigue performance have been observed with the addition of elastomeric polymers, reactive ethylene terpolymers, and other compatibilizers[43,44]. However, while LDPE-modified binders with a higher degree of branching show improved fatigue performance, their high-temperature performance tends to decrease compared to binders made with linear LDPE[45]. Nanoscale characterization of LDPE-modified binders suggests that incorporating crosslinkers and compatibilizers can enhance the stability of LDPE within the asphalt binder[46–48]. Furthermore, AC mixes prepared with LDPE-modified binders have demonstrated improved adhesive properties, Marshall stability, and air void content. However, they also show reductions in specific gravity, flow value, and voids in mineral aggregates[49–52].

Motivation and objectives

The increasing global emphasis on environmental sustainability has necessitated the exploration of alternative materials in pavement engineering, particularly the integration of recycled polymers such as low-density polyethylene (LDPE) into asphalt binders. While existing research has primarily focused on the rheological properties of LDPE-modified binders, there is limited research focusing on the mechanical performance of asphalt concrete (AC) mixtures incorporating LDPE-modified binders. Specifically, studies are lacking that evaluate critical mechanical properties such as stiffness, resistance to high-temperature permanent deformation, intermediate-temperature fatigue damage, and moisture-induced damage in AC mixtures containing LDPE-modified binders. Furthermore, to the best of the author's knowledge, none of the research studies have addressed the economic aspects of using LDPE-modified binders in pavement construction, including comparative analyses of construction costs associated with various binder types.

Therefore, this research study aims to fill these gaps by thoroughly investigating the mechanical properties and economic considerations of pavements designed with LDPE-modified binders alongside other commonly used binders. The following objectives were achieved after the completion of this experimental research:

1. Evaluation of the performance of asphalt concrete mixes prepared with LDPE-modified asphalt binders and compare their performance with those prepared with commonly used neat and modified binders.
2. Comprehensive analysis of the pavement designed with LDPE-modified asphalt binders using linear elastic layered theory.
3. Economic evaluation of the pavement designed with LDPE-modified asphalt binders and other conventionally used asphalt binders.

By addressing these research objectives, this study aims to make a significant contribution to sustainable pavement engineering. The findings will provide valuable insights into the potential of LDPE-modified binders to improve pavement performance while also offering a cost-effective and environment friendly alternative to traditional binders.

Materials

Aggregates

In this research study, sandstone aggregates were used to prepare asphalt concrete (AC) mixtures. These aggregates are readily available in different parts of India and are commonly used to construct flexible pavements. Before the mixture preparation, the quality of the aggregate was assessed. It was found to align with the criteria established by the Ministry of Road Transport and Highways (MoRTH) guidelines, a standard followed within India. The mechanical properties of aggregates used are shown in Table 1.

Plastics

LDPE plastic was used in this research study. This LDPE plastic was procured from a local recycler in the form of pellets. The plastic used was post-consumer recycled; a detailed description of post-consumer recycled plastics can be found in detail in other literature[8]. Before pelletization, these plastics were used as thin packaging material. The specific gravity of the plastic used is 0.932, and the melt flow index (MFI) is 8.57 g/10min. In contrast, the melting and crystallization temperatures are 145 °C and 55 °C, respectively, and the degree of crystallinity (DOC) calculated was 6.8%,following the procedure described by Audy et al[53]..

Asphalt binder

This research explores the performance of five different asphalt binders. These include LDPE-modified asphalt binder (referred to as LDP), SBS-modified asphalt binder (commonly known as PMB 40, where '40' indicates its penetration value), and crumb rubber-modified asphalt binder (CRMB – 60, where '60' denotes its softening point in degrees). Two neat/unmodified viscosity grade (VG) binders, VG 30 and VG 40 are standard asphalt binder grades in India. The numbers '30' and '40' signify their absolute viscosities at 60 ℃, ranging from 2400 to 3600 poises and 3200 to 4800 poises, respectively. PMB 40 and CRMB 60 are the commonly used modified binders in India. PMB 40, CRMB 60, VG 30, and VG 40 are readily available asphalt binders in the Indian market and are primarily used for paving purposes based on traffic loading. Table 2 represents the index properties of asphalt binder used in the research study.

Preparation of LDPE-modified binder

The process involved modifying the base asphalt binder, VG 30, by blending it with LDPE pellets with a weight ratio of 3% to the base asphalt binder. Before mixing, LDPE pellets were thoroughly washed and dried to remove any organic residues or impurities. Modifying asphalt binder began with heating 1500 g of base binder in a covered container at around 160 °C, with slow stirring for 15 min to eliminate residual air bubbles and prevent foaming. After adding LDPE, the blends were mixed at 500–1000 rpm for 15 min at the same temperature to ensure melting of plastics. The mixing rate was then increased up to 3500 rpm, followed by slow mixing of another 10 min maintaining a temperature between 160 and 180 °C for another hour to ensure proper blending and dispersion of plastics in binder matrix[1]. The mixing was done by keeping the container closed from the top to reduce the binder's oxidative aging. Once the blending was complete, the modified asphalt binder was checked

Properties	Combined flakiness and elongation index	Los angeles abrasion value	Aggregate impact value
Limiting values	Max 35%	Max 40%	Max 30%
Test results	21%	19%	16.6%
Test protocol	IS:2386-Part I	IS:2386-Part IV	IS:2386-Part IV

Table 1. Mechanical properties of the aggregates used.

Asphalt binders	Penetration (dmm)	Softening point (℃)	Performance grade (high temperature) (℃)	Performance grade (intermediate temperature) (℃)
VG 30	65	48.5	64	22
VG 40	44	58.1	76	25
PMB 40	41	71	82	31
CRMB 60	48	61.5	76	28
LDP	42	64	82	28

Table 2. Index properties of asphalt binder used in the research.

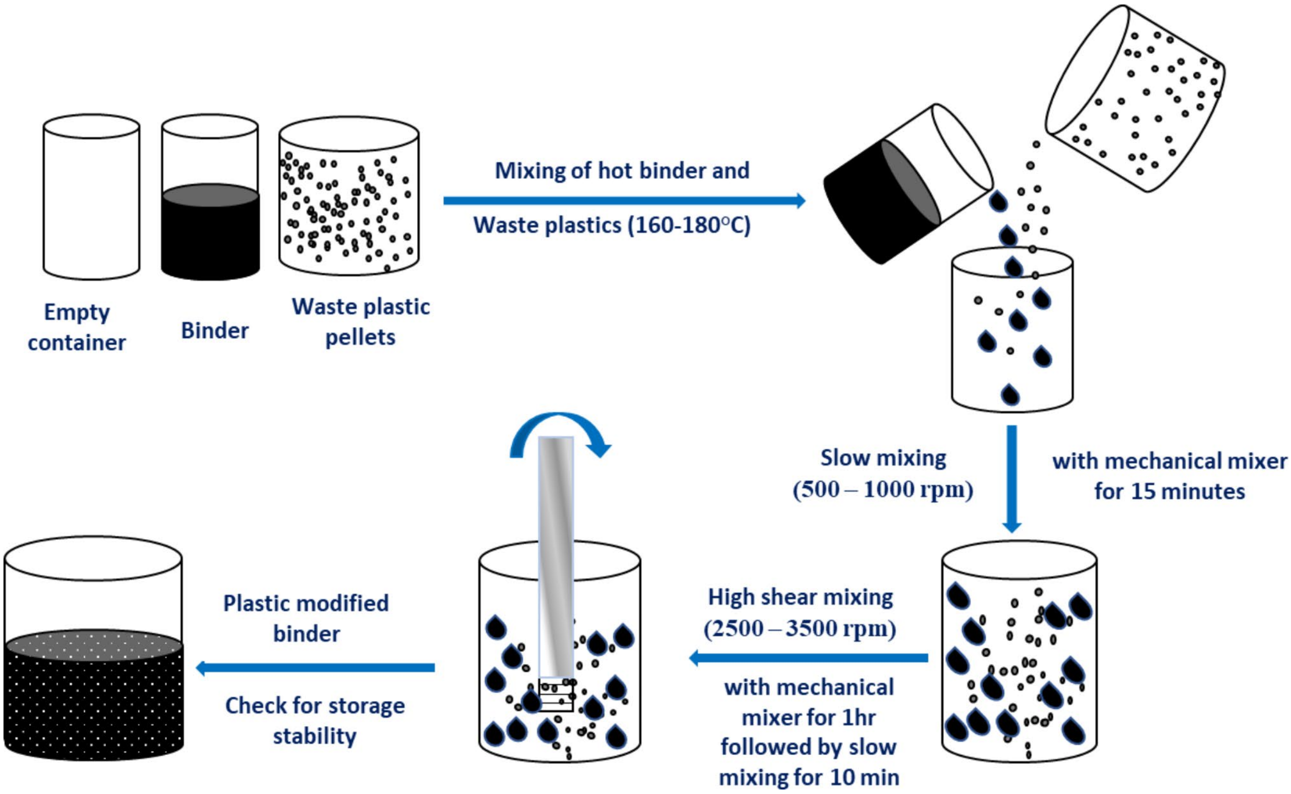


Fig. 2. Schematic representation of binder modification with LDPE.

for storage stability at high temperatures as per IS 15,462 – 2019 (India). The modified binder was found storage stable and further used to prepare asphalt mixtures. The proportion of 3% was optimized through the trial and error method. Above this plastic content, the modified binder showed phase separation. Figure 2 illustrates the procedure adopted for binder modification with LDPE.

Asphalt concrete mixture

In this research study, a bituminous concrete grade 1 (BC – 1) asphalt concrete (AC) mixture was prepared, adhering to the guidelines outlined by the Ministry of Road Transport and Highways (MoRTH). BC – 1 AC is specifically designed as a surface course mixture with a nominal maximum aggregate size of 19 mm. The aggregate gradation for the BC – 1 AC mixture was carefully selected to meet the requirements specified by MoRTH guidelines. The adopted aggregate gradation is shown in Fig. 3. In India, the design and performance evaluation of AC mixes is done on Marshall mix samples[50]. Therefore, the Asphalt Institute specifications, MS-2[54] were used for the Marshall mix design.

The same aggregate gradation was adopted for all the AC mixes prepared using different binders. For each mix, the calculated optimum binder content (OBC) has been shown in Table 3. AC mixes with different binders have been represented with the following names mentioned in Table 3.

Methodology and experimental program

The performance evaluation of asphalt mixes was conducted on samples prepared with 7 ± 0.5% air voids. The target air voids were achieved by varying the number of hammer blows during compaction. Additionally, to assess resistance to fatigue damage, evaluations were performed on long-term aged samples. The long-term

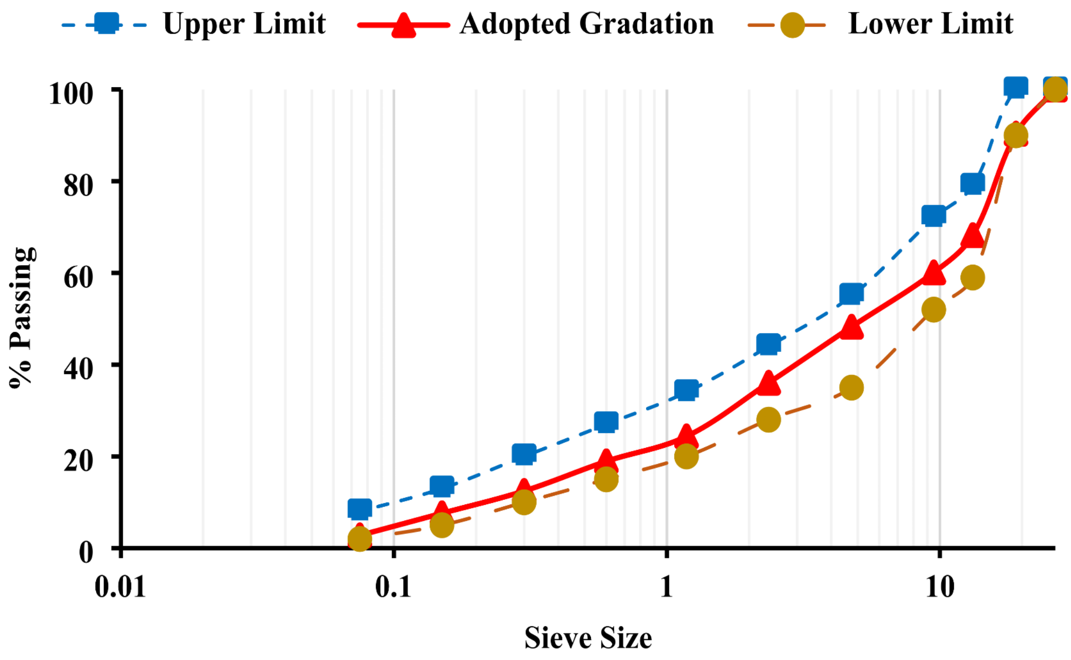


Fig. 3. Aggregate gradation adopted.

Ac mix	VG 30	VG 40	PMB	CRMB	LDP
Binder type	VG 30	VG 40	PMB 40	CRMB 60	LDP 3%
OBC (%)	5.70	5.62	5.75	5.79	5.59

Table 3. OBC of asphalt mixes at OBC.

aging of the asphalt mixes followed the guidelines outlined in AASHTO R 30, i.e., by placing them in the oven at 85 ± 3 °C for 120 ± 0.5 h. After 120 ± 0.5 h, turn the oven off, open the oven doors, and allow the test specimen to cool to room temperature. Figure 4 illustrates the methodology adopted in this research study.

Stiffness of the asphalt mix

Asphalt mixtures' stiffness was evaluated using the resilient modulus (M_r) test, as per ASTM D 4123–82. M_r measures the elasticity of the asphalt mixes by subjecting the mixture to stress and measuring recovered strain. As per the linear elastic layered theory, M_r is a crucial input parameter for pavement design[55]. M_r test was conducted on the samples, prepared using the Marshall method with various binders, at testing temperatures of 25 °C and 35 °C. A universal testing machine (UTM) with a temperature control chamber was used, and a load equivalent to 10% of the indirect tensile strength (ITS) value was applied. Samples were conditioned at the specified temperatures for 4 h to ensure consistency of temperature before testing. M_r test was performed on two axes and different samples for both temperatures. Three replicates for each temperature and binder type were tested on both axes. The reported M_r values are the average of six individual M_r values for each binder type and temperature.

Indirect tensile strength of AC mixes

Compacted asphalt mixes' indirect tensile strength (ITS) is associated with its resistance against cracking and was determined as per ASTM D 6931[56]. This test is carried out at 25 ℃ in which a Marshall specimen was loaded diametrically in compression using steel strips at a constant loading rate of 50.8 mm/min. To maintain a constant temperature of 25 ℃, the samples were kept in a water bath for 30–40 min at 25 ℃. A total of 15 samples (three per binder) were prepared, and mean ITS values were compared. The ITS values of the asphalt mixtures were evaluated using Eq. 1.

$$ITS = \frac{2000P}{\pi DT} \tag{1}$$

ITS = Indirect Tensile Strength, in kPa, P = Peak load, in N, T = Height of the sample, in mm, D = Diameter of the sample, in mm.

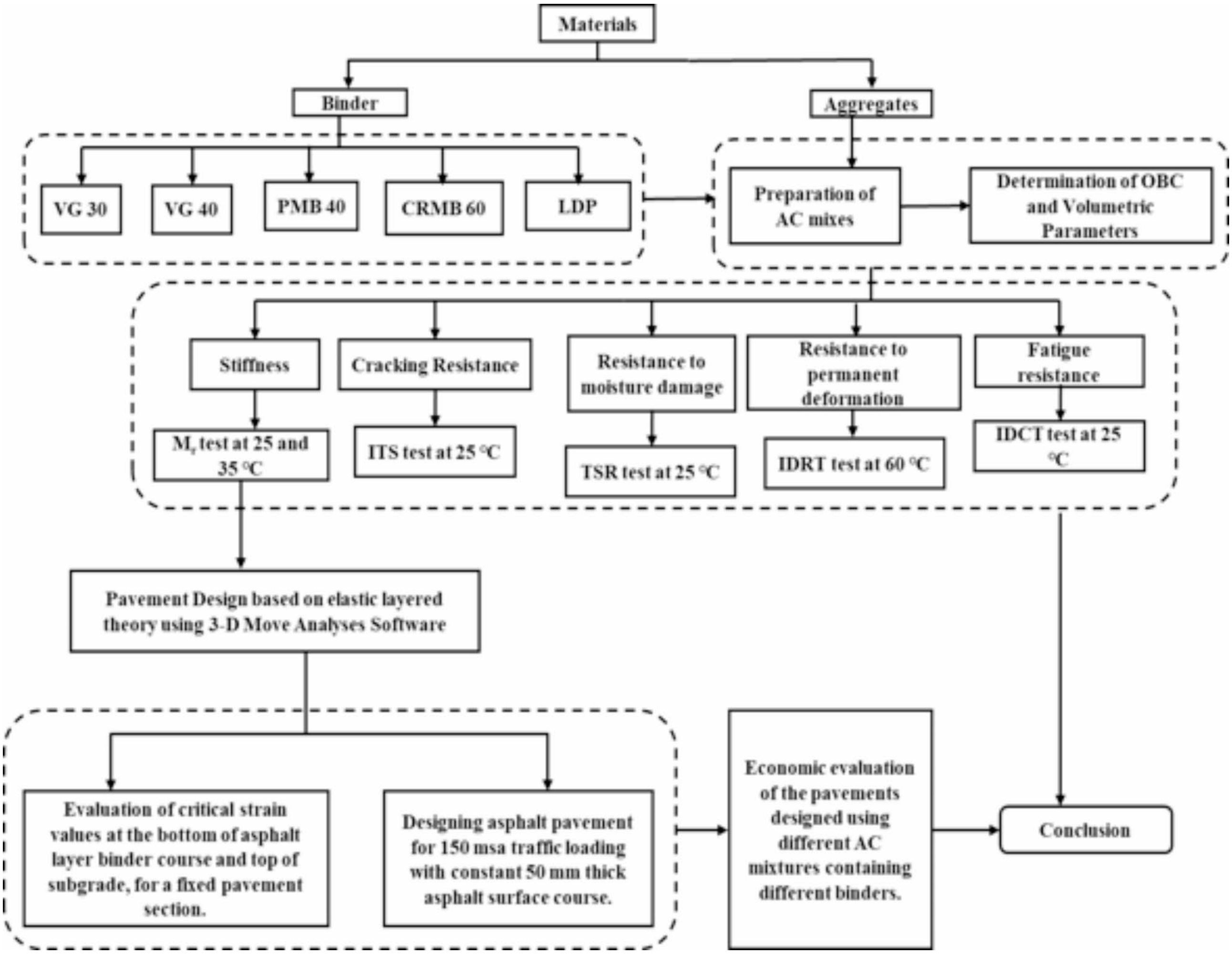


Fig. 4. Research methodology adopted in the study.

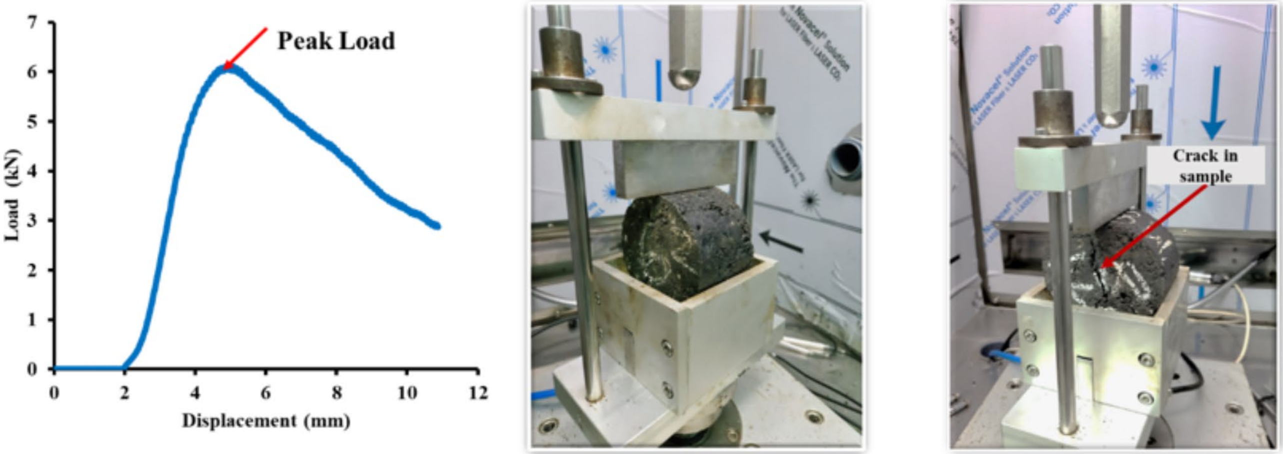
Susceptibility to moisture damage

The resistance to moisture damage in asphalt mixes was assessed through the tensile strength ratio (TSR) method[57], following the guidelines outlined in ASTM D 4867 M − 09. To calculate TSR, the ratio of ITS values of conditioned samples to unconditioned samples was determined (as per Eq. 2). Conditioning of the samples involved immersing them in a water bath at a constant temperature of 60 °C for 24 h. Subsequently, the samples were transferred to the water bath at 25 °C for an additional hour. For each mixture type, two sets were prepared, each comprising three samples. One set was conditioned, while the other set was subjected to a standard ITS test with conditioning for 30–40 min at 25 °C.

$$TSR = \frac{ITS_{Conditioned}}{ITS_{Unconditioned}} \tag{2}$$

Resistance to permanent deformation

The resistance to permanent deformation of asphalt mixtures is an important performance parameter to ensure a long-lasting pavement and was evaluated using the Ideal Rutting Test (IRT) in accordance with ASTM D8360–22 standard. A 101.6 mm diameter marshall sample with 7 ± 0.5% air voids has been used for the IRT test. Subsequently, the Rutting Tolerance Index (RT_{Index}), which measures resistance to permanent deformation, was calculated. A higher RT_{Index} value signifies the mixture's superior rutting resistance. Since permanent deformation is likely to occur at higher temperatures, the IRT test was conducted at 60 °C. This temperature encapsulates the highest observed service temperature in India, ensuring the test conditions' relevance to actual field conditions. The samples have been conditioned at test temperature for 2 h before testing. RT_{Index} has been evaluated using the Eqs. 3 and 4. A total of six samples of each mix have been tested to ensure the repeatability of the test, and the reported values are the average of these six samples. Figure 5 (a-c) illustrates the load vs. displacement curve, IRT test fixture, and a failed sample.



(a) (b) (c)

Fig. 5. (**a**) Load (P) versus load line displacement (l) curve; (**b**) Ideal rutting test fixture; (**c**) Failed sample after testing.

$$\tau_f = 0.356 \times \frac{P_{max}}{t \times w} \tag{3}$$

$$RT_{Index} = 6.618 \times 10^{-5} \times \frac{\tau_f}{1\,Pa.} \tag{4}$$

Where τ_f is the shear strength in Pa, P_{max} is peak load in N, t is the thickness of the specimen in mm, and w is the width of the upper strip (i.e., 0.0191 m).

Fatigue performance of asphalt concrete mixtures

To evaluate the fatigue performance of asphalt mixtures, 4-inch (101.6 mm) diameter marshall samples were prepared with $7 \pm 0.5\%$ air voids, and these samples were long-term aged as per AASHTO R 30 protocol. The fatigue performance of the AC mixtures was assessed using the Indirect Tensile Cracking Test (IDCT). The Cracking Tolerance Index (CT_{Index}) was calculated from the load-displacement curve. The CT_{Index} of an asphalt mixture is derived from the failure energy, the post-peak slope of the load-displacement curve, and the deformation tolerance at 75% of the peak load. The CT_{Index} is a performance indicator of the cracking resistance of asphalt mixtures, which may contain various asphalt binders, asphalt binder modifiers, aggregate blends, fibers, and recycled materials. Generally, a higher CT_{Index} value indicates better cracking resistance and, consequently, less cracking in the field. The acceptable range for the CT_{Index} varies with mix types and their specific applications. The CT_{Index} was evaluated at a test temperature of 25 ℃, as fatigue cracking is most likely to occur at intermediate temperatures. The test samples were conditioned at 25 ℃ for four hours before testing. CT_{Index} has been evaluated using the Eq. 5. A total of six samples of each mix have been tested to improve the repeatability of the test.

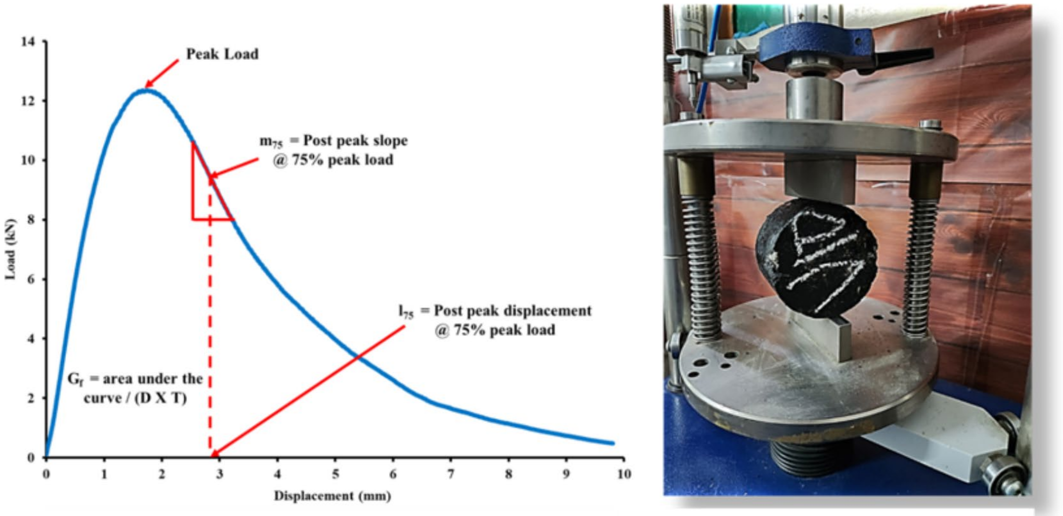
$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \tag{5}$$

Where t and D are the Height and Diameter of the sample in mm, respectively, G_f is the failure energy (Joules/m^2), m_{75} is the absolute post-peak slope (N/m), and l_{75} is the displacement at 75% the peak load after the peak in mm (as shown in Fig. 6 (a)), and 10^6 is the scale factor. Figure 6 (b) illustrates the test setup for IDCT test.

Pavement design

Conventional asphalt pavement has been designed with five different layers: subgrade, granular subbase, granular base, binder course, and surface course (as shown in Fig. 7). The thickness of each layer was chosen based on the guidelines of IRC: 37, 2018. The California Bearing Ratio (CBR) of the subgrade was assumed to be 8%, and this CBR value is then utilized to predict the M_r values of the subgrade, granular base, and subbase layers, following the guidelines of IRC 37, 2018, using Eq. 6, and 7. In the binder course, dense graded bituminous macadam (DBM) has been used, and the indicative M_r values given in IRC: 37, 2018 have been taken as input parameters. The M_r of the surface course is also determined experimentally, and the resulting values are used as input parameters. For pavement design, 35 ℃ is taken as the reference temperature since this is considered as the annual average pavement temperature for major parts of the country.

$$M_{rs} = 17.6 \times (CBR)^{0.64} for\ CBR > 5\% \tag{6}$$



(a) (b)

Fig. 6. (**a**) Load (P) vs. displacement curve with different parameters; (**b**) IDCT test setup used

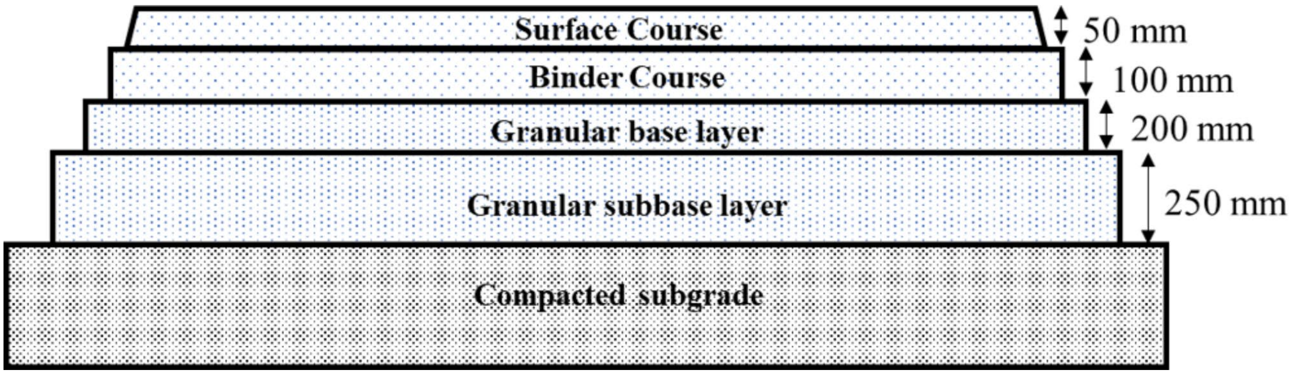


Fig. 7. Crossection of conventional pavement designed.

$$M_{r(granular)} = 0.2 \times \ (h)^{0.45} \ \times \ \ M_{rs} \tag{7}$$

Where M_{rs} is the M_r of subgrade, $M_{r\ (granular)}$ is the M_r of the granular layer combined, and h is the combined Height of the granular layer.

Pavement analysis and design using 3D-Move

3D Move analysis software has been used to evaluate the structural response of the pavement, which further uses a continuum-based finite-layer approach[58]. The 3D-Move Analysis model offers a comprehensive framework for evaluating critical pavement response factors. These include the complex 3D contact stress distributions (normal and shear) induced by moving traffic, vehicle speed, and the viscoelastic properties of pavement layers. This method treats each pavement layer as a continuous medium and utilizes the Fourier transform technique. Consequently, it addresses complex vehicular loading such as multiple loads and non-uniform stress distribution at the tire-pavement interface. Figure 7 shows the cross-section of the pavement analyzed using 3D-Move analyses software. Notably, the critical strain values are obtained, specifically horizontal tensile strain (ε_t) at the bottom of the AC layer (bottom of binder course) and compressive vertical strain (ε_z) at the top of the subgrade layer. Since rutting and fatigue are common distress types, the performance of the pavement was evaluated considering these two; subgrade rutting and AC fatigue life were calculated based on empirical relations (Eqs. 8–10) as prescribed for 90% reliability in IRC 37, 2018.

$$N_R = 1.41 \times \ 10^{-8} \left(\frac{1}{\epsilon_z}\right)^{4.5337} \tag{8}$$

$$N_f = 0.5161 \times C \times 10^{-4}\left(\frac{1}{\epsilon_t}\right)^{3.89} \times \left(\frac{1}{M_r}\right)^{0.854} \quad (9)$$

$$C = 10^M \; and \; M = 4.84\left(\frac{V_{be}}{V_a + V_{be}} - 0.69\right) \quad (10)$$

N_r is the rutting life of the subgrade (measured as a cumulative equivalent number of 80 kN standard axle load served by pavement before the rut depth of 20 mm or more), and ε_z is the vertical compressive strain at the top of the subgrade layer. N_f is the fatigue life of the asphalt layer (cumulative equivalent number of 80 kN standard axle load served by pavement before the critical cracks are of 20% or more), V_{be} is the percent volume of effective asphalt binder in the mix, V_a is air void in the mix (%), ε_t is the horizontal tensile strain at the bottom of AC layer, and M_r is the resilient modulus of the AC mix. N_r and N_f have been evaluated in millions of standard axle (msa) load repetitions.

Economic evaluation of pavements

In this research study, the laying cost of AC mixtures is evaluated. The pavement has been designed to sustain 150 msa loading. To achieve this, the thickness of the compacted subgrade layer, granular layers, and the surface course have been kept constant, as shown in Fig. 7. The only variable is the thickness of the DBM layer. The DBM layer is designed using a VG 40 asphalt binder, regardless of the surface AC mix. However, IRC: 37, 2018 does not permit using modified asphalt binders in binder course, since it jeopardizes recycling the binder course (DBM layers). Also, use of VG 30 binder for preparation of mixes for asphalt pavements is not advisable if traffic loading is above 50 msa. The critical strain values are calculated using 3-D move analysis software. Subsequently, rutting and fatigue life have been evaluated using Eqs. 8 and 9, respectively.

Also, for PMB and CRMB AC mixtures, the M_r values of the surface course and binder course were taken similar, as per the recommendation of IRC 37: 2018. This is because the elastic layered theory does not consider the viscoelastic properties of AC mixtures, and AC mixtures containing PMBs show delayed elastic recovery upon loading and unloading[59]. This leads to PMB's lower M_r values, which yields higher pavement thickness. In the end, the laying cost of AC layers was evaluated for a single lane of 3.5 m width and 1000 m length. The tentative laying cost of AC mixtures per cubic meter has been shown in Table 4. These costs were obtained after discussion with different contractors and government tendering authorities. Since these costs depend on many factors, thus they tend to vary regionally, but the trends of the prices will remain the same.

Results and discussion

Stiffness of the asphalt concrete mixtures

The M_r of asphalt mixes has been evaluated and shown in Fig. 8. The stiffness of the LDP asphalt mixtures was observed to be highest, compared to all other mixtures, irrespective of testing temperatures. The reduction in stiffness with an increase in temperature was lower in virgin binder mixes than in modified binder mixes. Among the other modified mixes, LDP shows the least temperature susceptibility. The M_r values decrease with the increase in temperature; the LDP AC mix shows the least reduction in M_r (i.e., 39.12%) compared to other modified AC mixtures, i.e., PMB and CRMB with 60.29 and 47.38%, respectively. Since M_r is a significant input parameter for pavement design, stiffer mixes can withstand higher load repetitions at a similar thickness. Consequently, the pavement thickness can be reduced for a given traffic load, leading to cost savings.

Tensile strength and moisture susceptibility of asphalt mixes

The cracking resistance and tensile strength of asphalt mixes was evaluated using the ITS test. A higher ITS value of the mix signifies its superior resistance to cracking[56]. ITS values of all mixes are illustrated in Fig. 9. The cracking resistance of PMB and LDP mixes was higher than all other mixes. LDP shows the highest resistance to cracking at intermediate temperatures.

Moisture sensitivity of the AC mixtures prepared with different types of asphalt binders was assessed using the tensile strength ratio (TSR) parameter. In this research, sandstone aggregates were used, which were locally available and readily used for paving purposes. As per literatures, the sandstone aggregates have higher affinity to the water than binder, and the bonding between the aggregates and binder is low[60]. It's commonly observed that the TSR values of these mixes were usually low, and they tend to fail early under the influence of moisture. Thus, researchers advise that antistripping agents be used to improve such mixes' resistance to moisture damage.

In this study, none of the antistripping agents were used to properly assess the influence of binder type on the moisture resistance of the mixtures. Figure 9 shows the TSR values of different mixes, and it can be observed from the test results that the TSR value for the LDP mix is the highest among all other mixes. Also, the plastic-

Binder type	Surface course (BC 1) (in us \$)	Binder course with vg 40 (DBM) (in us \$)
VG 40	156.62	138.55
PMB	204.82	
CRMB	183.74	
LDP	172.3	

Table 4. Laying cost of AC layers in India.

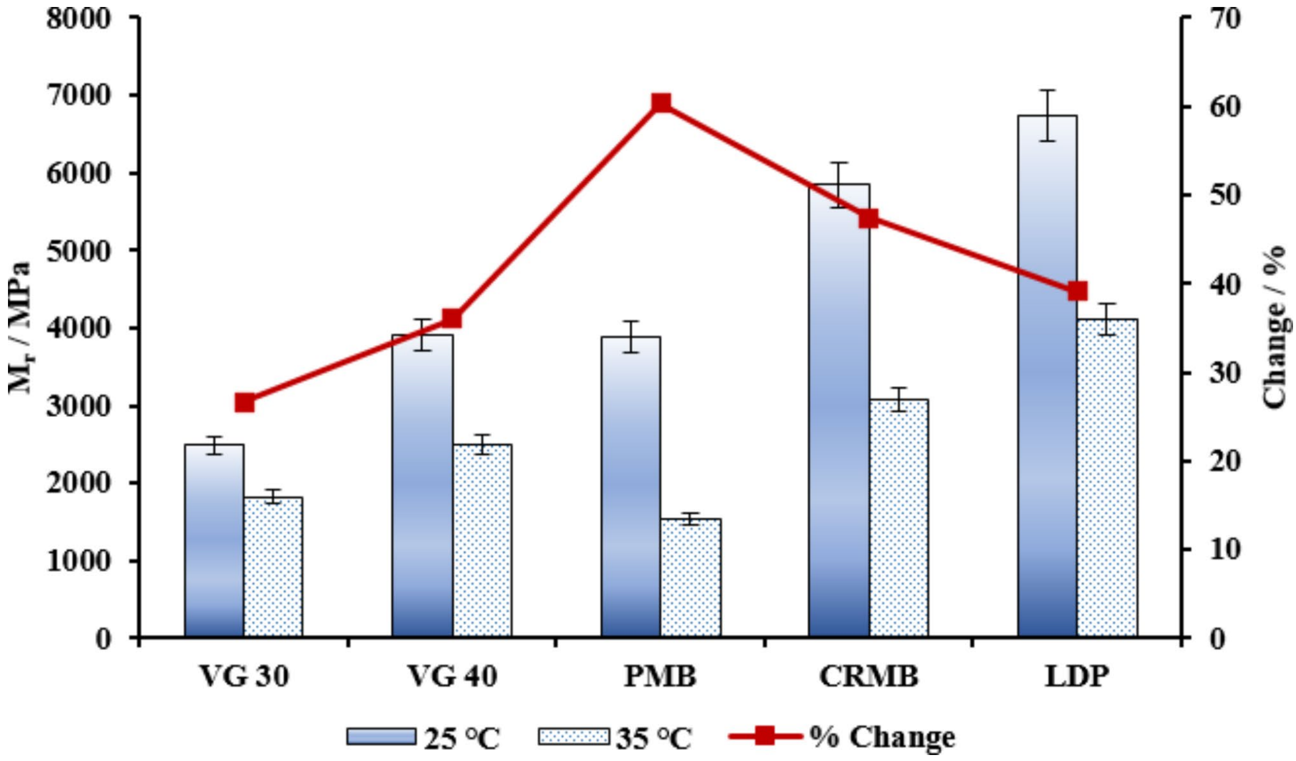


Fig. 8. Resilient modulus of asphalt mixes.

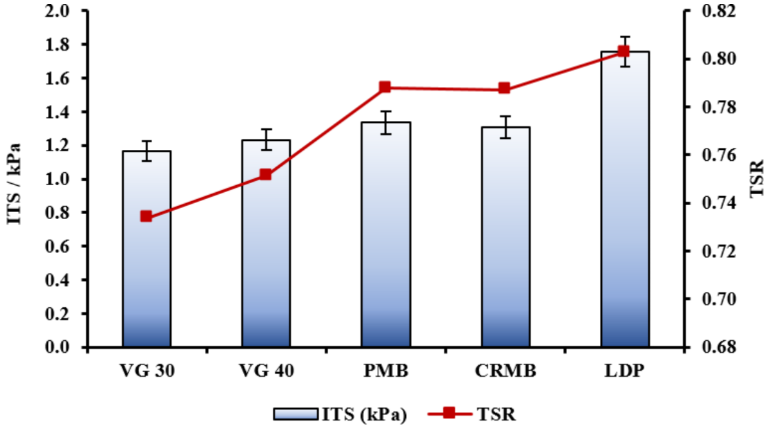


Fig. 9. ITS and TSR results for asphalt mixes.

modified binder offers enough resistance to moisture damage since TSR values are above 0.80 for the plastic-modified mixtures.

Permanent deformation susceptibility of asphalt mixes

Resistance to permanent deformation of asphalt mixes has been evaluated using the IRT test. Figure 10 shows that the LDP mixes show the highest RT_{Index}. Also, the peak load relates to the stiffness of the mixture. Higher the peak load, stiffer the mixture[61]. Moreover, LDP mix shows the highest peak load at failure, which signifies that the LDP mix can sustain the highest load before failure amongst all other mixes. Whereas, CRMB, VG40, and PMB mixes offer similar performance per the RT_{Index} test. Since the IRT test involves continuous loading rather than cyclic loading, thus the recovery properties of the PMB and CRMB mixture have not been taken into account. Previous literatures have suggested that PMB and CRMB mixtures offer much higher resistance to permanent deformation in actual field conditions than other AC mixes containing unmodified/virgin binders[40,62].

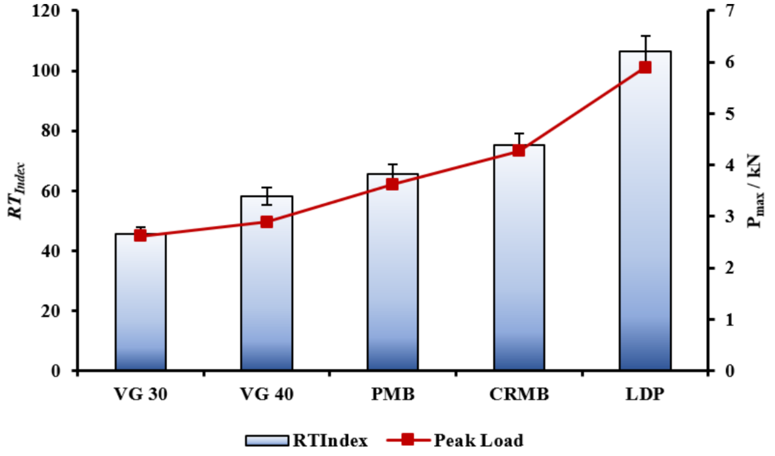


Fig. 10. RT_{Index} and Peak load obtained from IRT test.

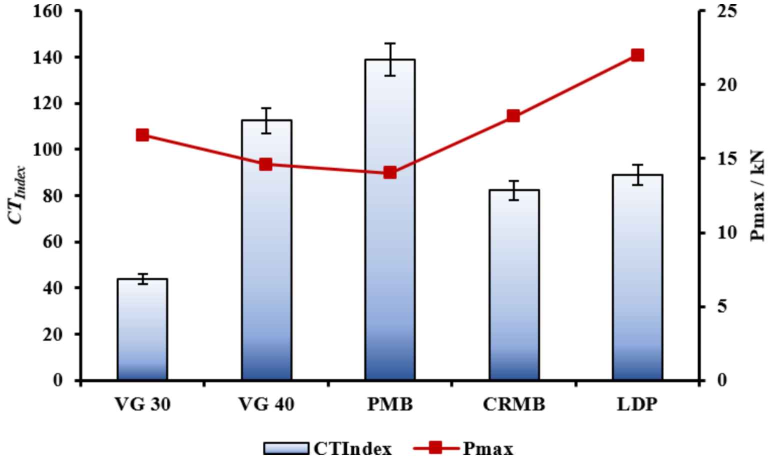


Fig. 11. CT_{Index} and $P_{\max}$ values of asphalt mixes.

Fatigue performance of asphalt concrete mixes

The CT_{Index} was evaluated at a test temperature of 25 ℃, given that fatigue cracking is most likely to occur at intermediate temperatures. Although $CT_{Index}$is generally used as a material screening test, in this research study, it is used to assess the intermediate fatigue cracking of AC mixes. Also, it is more insightful to evaluate different parameters individually rather than showing a load-displacement curve[63]. As shown in Fig. 11, PMB 40 mixes showed the highest CT_{Index} value, signifying that the PMB 40 mixes possess the highest fatigue resistance, followed by VG 40, LDP, and CRMB mixes. LDP mixes showed lower fatigue resistance than other mixes except VG 30. This can be attributed to higher stiffness which can be characterized by higher peak load to failure (as shown in Fig. 11). The CT_{Index} values of LDP mixes are 103 and 8.3% hgher than VG 30 and CRMB AC mixtures, whereas 21 and 36% lower than VG 40 and PMB AC mixtures respectively.

The P_{max} was the highest for LDP mixes, which shows that the highest load is required to crack the LDP AC mix. However, lower CT_{Index} and higher P_{max} signify the brittle failure of the samples. Also, the l_{75}/D parameter of LDP is lower than PMB, and CRMB AC mixes, and the post-peak slope (m_{75}) is lower than the CRMB AC mixture. Higher m_{75} shows a higher crack growth rate after peak load, resulting in lower CT_{Index} (Abdalfattah et al., 2022). Furthermore, along with the CT_{Index} of mixtures, binder type may affect two additional parameters: the Strain Tolerance Parameter (l_{75}/D) and fracture energy (G_f). The l_{75}/D parameter quantifies the strain tolerance under an applied load and is a reliable indicator of the mixture's ductility[64]. With an increase in the l_{75}/D value, the mixture shows improved ductility, which further reduces the cracking susceptibility of mixes. LDP shows lower l_{75}/D parameter values than VG 40, PMB, and CRMB AC mixes.

Essentially, any modifier that increases the stiffness of the AC mixture and is subjected to the same displacement control load rate will experience a faster accumulation of stress during the test, consequently leading to a less ductile mode of failure. However, it's imperative to note that this effect is a consequence of the displacement-controlled testing method and may not accurately represent the material's behavior under stress-controlled tests[63].

Figure 12 (a) shows the fracture energy (G_f), and (b) represents the strain tolerance factor (l_{75} / D). G_f is calculated by evaluating the area under the load-displacement curve divided by the area of the cracked surface. G_f represents the energy needed to initiate a crack per unit area. Conclusively, G_f indicates the resistance to crack propagation[65]. Thus, a higher G_f indicates higher resistance to crack propagation, reflecting a higher energy requirement for cracking. The IDCT test is conducted in a displacement-controlled mode.

Pavement design using 3D move analyses

A conventional AC pavement was designed, with different mixes used in the surface course while maintaining constant properties for all other layers (as shown in Fig. 7). The thickness of the surface course has been fixed to 50 mm, only the asphalt mixture containing different binders has been changed. Furthermore, the thickness of the surface course and AC mixture type in the binder course was kept constant for all the other mixes containing different binders except the surface course containing the VG 30 binder mixture. For this, the binder course is also prepared with a VG 30 binder.

The M_r values of the binder course were assumed as 3000 MPa for DBM mixes containing VG 40 binder at 35℃, which IRC 37: 2018 has recommended for pavement design. The granular base layer and subbase layer have been considered as single layers since both share similar aggregate gradation, material properties, and M_r values. Deformation (δ) at various pavement layers, including the pavement surface, bottom of the surface course, bottom of the AC layer, and top of the subgrade layer, was determined as shown in Fig. 13 (a). N_r and N_f values were also calculated using Eqs. 8 and 9 from the strain values obtained from 3D Move analyses (as shown in Fig. 13 (b)).

Figure 13(a) shows that the LDP mix shows the lowest deformation at all the interfaces, followed by CRMB. The difference between the δ values is most notable nearer to the surface and reduces with subsequent layers. Here, PMB and VG 30 AC mixtures show higher deformation; this can be attributed to the lower stiffness of the VG 30 binder, which makes it unsuitable for higher traffic loading. In the case of PMB AC mixtures, although the deformation is higher, the recovery is also high due to the presence of elastomers, which eventually leads to lesser deformation[66]. However, this behavior of PMB has not been accounted for in pavement design using elastic layered theory, underscoring the importance of considering the viscoelastic properties of AC mixtures as input parameters in pavement design[58].

When N_r and N_f values are considered, LDP AC mixtures exhibited higher N_r and N_f values than other primarily used AC mixtures. Fatigue is the predominant parameter in this conventional pavement design, as shown in Fig. 13 (b). The designed pavement containing LDP AC mixture shows 57, 7.66, 23, and 7.07% higher fatigue life than VG 30, VG 40, PMB, and CRMB AC mixtures. At the same time, pavement containing LDP AC mixture yielded 42.33, 15.81, 40.23, and 14.54% higher N_r values than VG 30, VG 40, PMB, and CRMB AC mixtures, respectively.

Economic assessment of the pavements

AC pavements have been designed to sustain 150 msa traffic loading, and critical strains have been assessed using 3D Move analysis software. These strains have been used to calculate the N_r and N_f values using Eqs. 8–10. The thickness of the DBM layer is reduced with the LDP surface layer (i.e., 145 mm), whereas in other cases, the thickness of the DBM layer remains the same, i.e., 155 mm. Consequently, the estimated laying cost of the AC layer per lane per kilometer decreases (as shown in Fig. 14). The reduction observed was 4.3, and 9.5% from the initial construction cost of AC layer containing CRMB and PMB AC mixtures as surface layers respectively, and similar costing as per VG 40.

The utilization of LDP AC mixtures reduces the cost of pavement construction. It facilitates the recycling of 750 kg of plastics per lane per kilometer. Although the amount of plastic waste seems less in terms of the

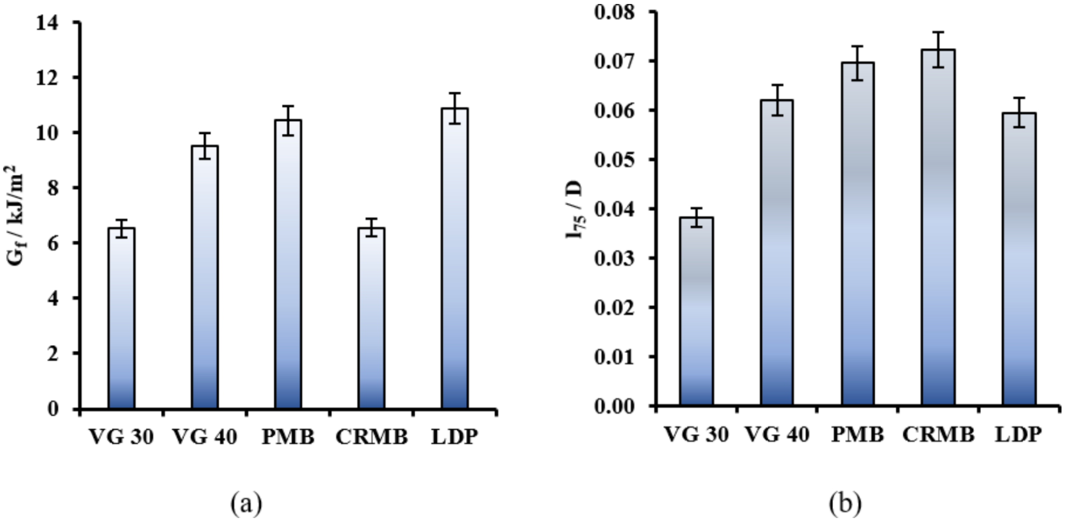


Fig. 12. (**a**) Fracture energy (G f); (**b**) l_{75}/D and post-peak slope ($|m_{75}|$).

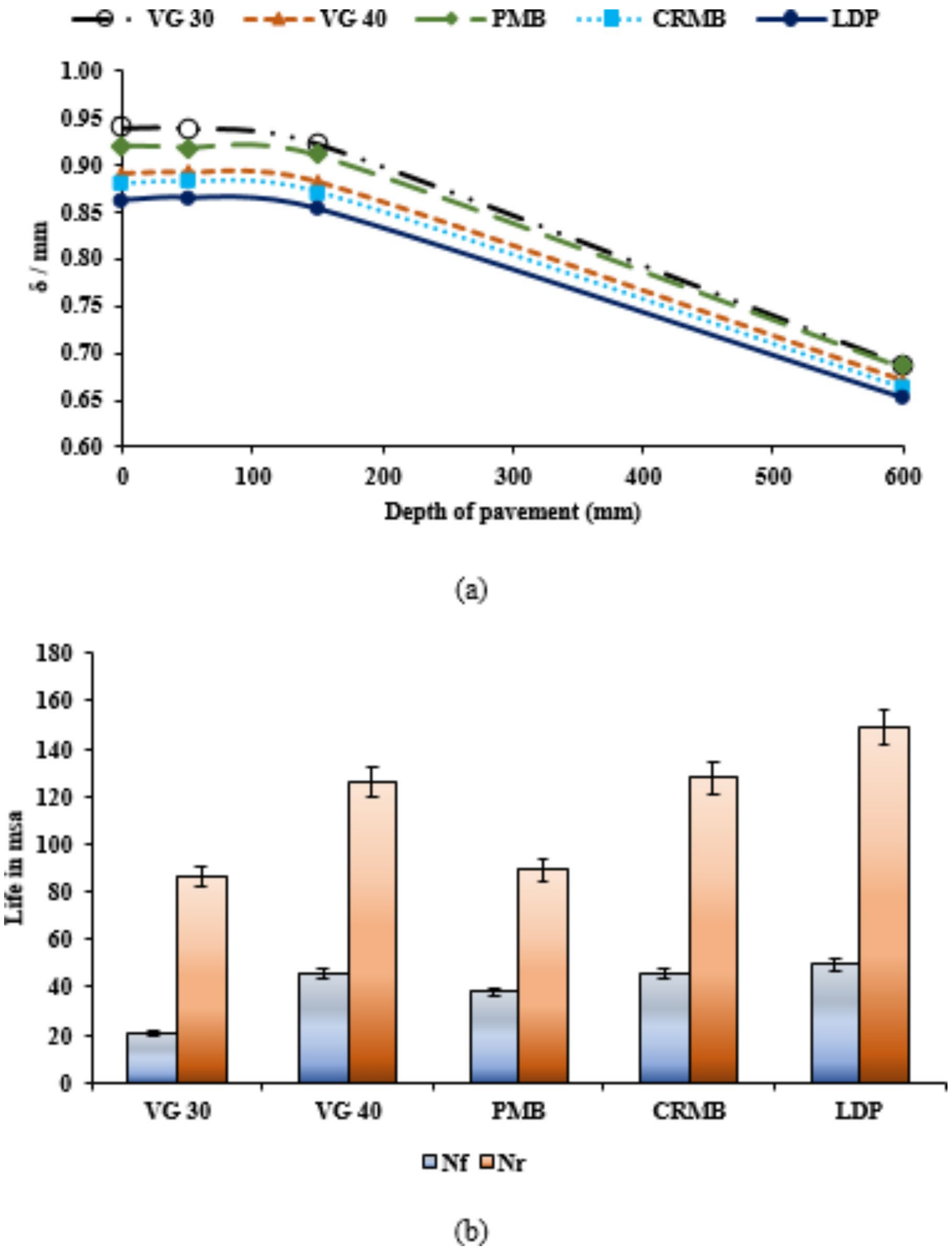


Fig. 13. Pavement response from 3D Move Analyses (**a**) Deflection with traffic loading in each layer, (**b**) N_r and N_f values.

money required to dispose of this plastic using conventional methods. But when the societal cost of plastic is considered, this method represents a significant amount of repurposing plastic material. A report submitted to the world wide fund for nature (WWF) in 2021 shows that the societal cost of waste plastic pollution ranges from \$149 to \$17 per kg, spanning low-income and high-income countries, respectively[67]. This societal cost encompasses greenhouse gas (GHG) emissions, the expenses associated with the collection and management of plastic waste, soil pollution attributed to plastics, and the ecological harm inflicted on marine environments

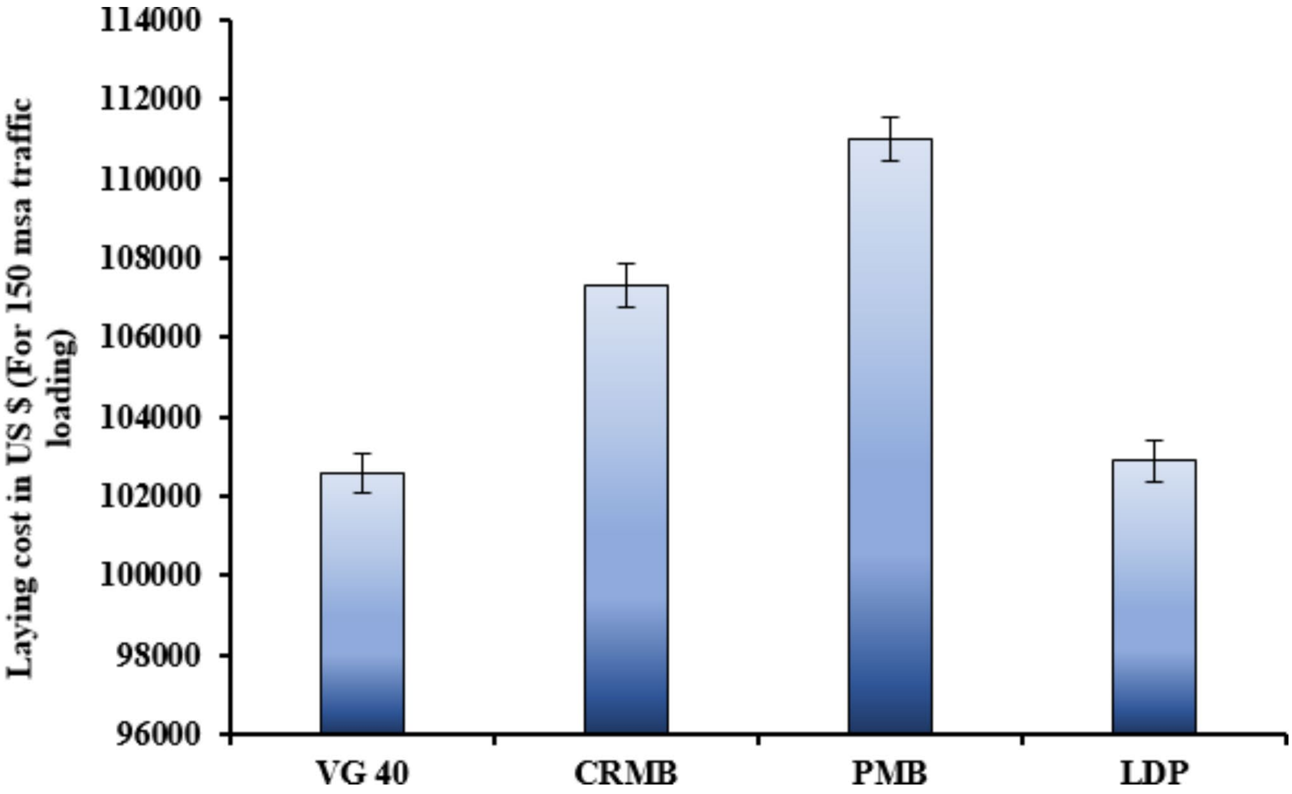


Fig. 14. Laying cost of AC layer with different surface layers.

Parameter	df	Mean square	F-calculated	*P*-value
ITS	29	1.11	17.45	2.60×10^{-04}
TSR	19	1.11	22.29	1.70×10^{-04}
M_r @ 25 ℃	59	618560.20	422.39	2.62×10^{-28}
M_r @ 35 ℃	59	428885.55	233.17	5.54×10^{-22}
CT_{Index}	59	532.15	153.19	6.65×10^{-15}
RT_{Index}	59	220.69	108.45	4.77×10^{-09}

Table 5. Summary of one-way ANOVA at 95% confidence interval.

by the disposal of plastic waste. In low-income countries, the lack of infrastructure for plastic waste recycling contributes to higher costs compared to those in high-income countries.

Statistical analysis

Several designs of experiment (DOE) methods, such as Analysis of Variance (ANOVA) and factorial analysis, are widely used in material engineering for statistical analysis[60,68]. In this research study, one-way ANOVA was applied to determine the effect of asphalt binder type on the ITS, TSR, M_r, CT_{Index}, and RT_{Index} values of AC mixes. These parameters measure different mechanical performances of AC mixes. Table 5 shows the results of the one-way ANOVA at a confidence level of 95% ($\alpha = 0.05$). The effect of the binder type will be considered significant when the p-value is less than 0.05. All the parameters show significant sensitivity to the type of binder used for the preparation of the AC mix. M_r parameter shows the highest sensitivity to the binder type, followed by CT_{Index}, RT_{Index}, ITS, and TSR.

Conclusions and future scope of research

The primary objective of this experimental research study is to assess the suitability of LDPE-modified asphalt binder modifier in AC mixtures. The focus is evaluating the mechanical performance and susceptibility to moisture damage, comparing them against conventional AC mixtures prepared with different commonly used binders. Additionally, economic analyses are conducted to complement the experimental investigation. In summary, the results showed that LDPE-modified asphalt mixes offer superior mechanical performance and cost-effectiveness in construction.

The following are some of the findings from the research study:

1. Introducing LDPE-modified asphalt binder into AC mixtures increases their stiffness compared to the AC mixtures prepared with VG 30 base binder by 171 and 125% at 25 and 35℃, respectively. However, it also increases the susceptibility to temperature variations. LDP mixes show higher stiffness across different temperatures, with LDP AC mixes showing higher temperature susceptibility (characterized by a lesser reduction in stiffness) than VG 30 (26.64%) and VG 40 (36.09%) and lower than Polymer-Modified Binder (PMB) (60.29%), and Crumb Rubber Modified Binder (CRMB) (37.08%) AC mixes.
2. Using LDPE-modified binder to prepare mixes increases the tensile strength of AC mixtures compared to the base binder by 51.11%. LDP AC mixtures show the highest Indirect Tensile Strength (ITS) values among all asphalt binders, indicating higher cracking resistance. Additionally, LDPE addition improves resistance to moisture damage, as evidenced by higher Tensile Strength Ratio (TSR) values i.e., 0.80. TSR value for LDP AC mixes exceeds those of all other studied mixes.
3. Using LDPE-modified asphalt binder in an AC mixture shows improvement in resistance to permanent deformation and fatigue at high and intermediate temperatures, respectively, compared to the base binder. LDP AC mixtures showed higher resistance to permanent deformation than all other studied mixtures. While higher fatigue resistance was observed compared to VG 30 and CRMB mixes, and lower resistance was observed compared to PMB and VG 40 mixes.
4. The improvement in resistance to permanent deformation is characterized by an increase in RT_{Index} values, LDPE modified AC mixes show 133.46, 82.30, 62.43, and 41.13% higher RT_{Index} values compared to VG30, VG40, PMB, and CRMB mixes, respectively. Fatigue resistance of AC mixes, assessed by CT_{Index} values. LDPE-modified mixes show 103.60 and 8.3% higher CT_{Index} values compared to VG 30 and CRMB mixes, respectively, whereas 26.32 and 56% lower CT_{Index} values compared to VG 40 and PMB mixes, respectively.
5. When pavement is designed using 3D Move Analyses software, the section containing LDP mix as surface course showed overall reduced deformation irrespective of the depths. Furthermore, higher N_r and N_f values than other studied mixes (VG 30, VG 40, PMB, and CRMB) were calculated for the similar cross-section of pavements. The LDP mixture showed 57%, 7.66%, 23%, and 7.07% higher N_f values and 42.33%, 15.81%, 40.23%, and 14.54% higher N_r values than VG 30, VG 40, PMB, and CRMB mixtures, respectively.
6. Economic analyses showed that the total cost of AC layer containing LDP as a surface course is similar to the VG 40 mix as surface layer. However, it was 4.3 and 9.5% more economical than the AC layer containing CRMB and PMB as surface course. Additionally, using LDP as a surface course uses 750 kg of plastic waste for a 3.5 m width lane and 1000 m section, with 50 mm thickness, which is an additional cost saving. The societal cost of waste plastic pollution saved is $149-17$ US $, for low-income and high-income countries, respectively.

Overall, the results show that using LDPE-modified binder in the production of AC mixes results in improved resistance to permanent deformation. The LDPE-modified binder is likely to increase the tensile strength of AC mixtures at the expense of some loss in ductility. The introduction of an elastomeric polymer co-modifier might mitigate this loss of ductility. However, none of these co-modifiers has been used in this study but can be done in the future. This co-modifier also helps improve the low-temperature performance of AC mixes containing LDPE. It will also enhance the dispersion of LDPE into the binder matrix and the stability of the binder. It's important to note that these experiments were conducted using a uniform LDPE sample from a single source. The performance of LDPE modified binder varies with changes in the sources of plastics, which might affect the performance of AC mixture. Future research endeavors should take this into account. Furthermore, this research study reports laboratory test results, the in-situ performance evaluation of the LDPE-modified mixtures may yield different performance results than the experimental results. Therefore, field evaluation should precede implementation.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available since it is an original laboratory study. But are available from the corresponding author on reasonable request.

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Author contributions

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Declarations

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Additional information

Correspondence and requests for materials should be addressed to A.G.