Performance Study of Polymer Modified Asphalt for Durable Pavements

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Abstract
The rapid growth in traffic volume coupled with wide climatic variations in India has intensified the demand for durable and high-performance pavement materials. Conventional VG-40 bitumen often exhibits premature distress, such as rutting and fatigue cracking, under high temperatures and heavy traffic loading. This study presents a comparative performance evaluation of Polymer Modified Bitumen (PMB RG 70-10E) and VG-40 binder used in Bituminous Concrete (BC-2) mixes, in accordance with MoRTH (5th Revision, 2013) specifications. A comprehensive laboratory investigation was conducted, including Marshall Stability and Flow, Indirect Tensile Strength (ITS), Resilient Modulus, and Dynamic Creep tests, to assess the mechanical behavior and durability of the mixes. The Optimum Bitumen Content was determined as 5.4% for VG-40 and 5.6% for PMB RG 70-10E. Experimental results demonstrate that PMB-modified mixes achieved approximately 18.4% higher Marshall stability, 35% improvement in ITS, and 54% increase in resilient modulus compared to VG-40 mixes, along with substantially lower permanent deformation under repeated loading. The improved performance is attributed to the enhanced elastic recovery, cohesive strength, and binder–aggregate bonding characteristics of PMB, which contribute to improved fatigue resistance and reduced temperature susceptibility. Overall, the findings confirm that PMB RG 70-10E offers superior strength, durability, and deformation resistance, making it a viable and effective binder for long-life and heavy-duty flexible pavements under Indian traffic and climatic conditions.

Keywords: Flexible Pavement, Modified Polymer, Marshall Stability, Modulus of Resilient, Indirect Tensile Strength Ratio, Dynamic Creep, etc.

Introduction

Flexible pavements form the backbone of road transportation infrastructure in India, accounting for more than 95% of the total road network. These pavements are primarily designed to distribute traffic loads safely to the subgrade while ensuring adequate riding comfort and long-term serviceability. Among the various layers of a flexible pavement system, the bituminous concrete (BC) layer is the most critical, as it directly resists traffic-induced stresses and environmental actions. However, the performance of flexible pavements in India has increasingly come under stress due to rapid urbanization, industrial growth, and a substantial rise in vehicular traffic over the past few decades.

The steady increase in commercial vehicle population, higher axle loads, overloading practices, and frequent stop–start traffic conditions have resulted in pavement sections being subjected to stress levels far exceeding those considered during design [1-2]. In addition, India experiences extreme climatic variations, ranging from very high surface temperatures exceeding 60 °C in summer to low temperatures in certain regions during winter, along with heavy monsoonal rainfall. These factors accelerate pavement deterioration, leading to premature distresses such as rutting, fatigue cracking, thermal cracking, ravelling, and moisture-induced damage [3-4]. Such failures not only reduce pavement service life but also impose significant economic burdens due to frequent maintenance and rehabilitation requirements.

Conventional paving-grade bitumen, such as VG-30 and VG-40, is widely used in Indian road construction. VG-40 is generally preferred for heavy traffic corridors due to its higher viscosity and stiffness at elevated temperatures. Nevertheless, several studies have shown that even VG-40 exhibits inherent limitations in elasticity, resistance to permanent deformation, and durability under severe loading and environmental conditions [5]. At high pavement temperatures, unmodified bitumen tends to soften excessively, making it susceptible to rutting and shoving. Conversely, at lower temperatures, it becomes brittle, increasing the likelihood of thermal and fatigue cracking [6]. Aging of bitumen due to oxidation further degrades its rheological properties, resulting in reduced flexibility and increased stiffness over time.

The rheological behaviour of the binder plays a crucial role in governing the overall performance of bituminous mixtures. Binder properties such as viscosity, stiffness, elasticity, and temperature susceptibility directly influence the load-carrying capacity, deformation resistance, and cracking behaviour of asphalt mixtures [7]. Conventional VG-grade binders exhibit predominantly viscous behaviour at high service temperatures, which limits their ability to recover deformation after load removal. This lack of elastic response is one of the primary reasons for rutting in heavily trafficked pavements [8]. Moreover, inadequate adhesion between the binder and aggregates can lead to moisture-induced stripping, especially in regions experiencing prolonged rainfall and poor drainage conditions.

To address these challenges, the modification of bitumen using additives and polymers has emerged as an effective and widely adopted approach. Polymer Modified Bitumen (PMB) has gained considerable attention due to its ability to enhance both elastic and viscoelastic properties of the binder. Polymer modification alters the microstructure of bitumen by forming a network that improves resistance to deformation, enhances elastic recovery, and reduces temperature susceptibility [9-10]. As a result, PMB exhibits superior performance compared to conventional binders, particularly under heavy traffic and high-temperature conditions.

A wide range of polymers has been used for bitumen modification, including elastomers such as Styrene Butadiene Styrene (SBS), Styrene Butadiene Rubber (SBR), and plastomers such as ethylene–vinyl acetate (EVA) and polyethylene. Elastomeric polymers primarily improve elasticity and fatigue resistance, while plastomeric polymers enhance stiffness and rutting resistance [11-12]. Among these, SBS-modified bitumen has been extensively studied and reported to provide an optimal balance between stiffness and flexibility over a wide temperature range. The enhanced elastic recovery of PMB enables the pavement to withstand repeated traffic loading without accumulating excessive permanent deformation [13].

Several laboratory and field studies have demonstrated that PMB significantly improves the performance characteristics of bituminous mixes. Improved Marshall Stability, higher indirect tensile strength, increased resilient modulus, and superior resistance to rutting and fatigue cracking have been consistently reported for PMB-modified mixes compared to conventional mixes [14-16]. In addition, polymer modification enhances binder–aggregate adhesion, thereby reducing moisture susceptibility and stripping potential [17]. These improvements contribute to longer pavement service life and reduced life-cycle costs, despite the higher initial cost of PMB.

Recognizing the performance benefits of polymer modification, Indian road authorities have incorporated PMB into national specifications and guidelines. The Ministry of Road Transport and Highways (MoRTH) recommend the use of PMB for wearing and binder courses subjected to heavy traffic and severe climatic conditions, particularly on national highways, expressways, and urban arterial roads [18]. IS 15462:2019 provides detailed specifications for polymer and rubber modified bitumen, including requirements for penetration, softening point, elastic recovery, and storage stability [19]. Performance evaluations conducted by research institutions such as the Central Road Research Institute (CRRI) and Indian Institute of Technology (IIT) have further validated the suitability of PMB for Indian conditions [20].
Despite these advancements, the selection of an appropriate binder for a given pavement application remains a complex task. The performance of PMB depends on several factors, including polymer type, polymer content, base bitumen properties, mixing and compaction temperatures, and aggregate characteristics. Inappropriate selection or improper handling of PMB can lead to issues such as phase separation, workability problems, and construction challenges [21]. Therefore, systematic laboratory investigations are essential to evaluate the performance of specific PMB grades in comparison with conventional binders under controlled conditions.
Bituminous Concrete Grade 2 (BC-2) is one of the most commonly used wearing course mixes in India. Laboratory performance tests such as Marshall Stability and Flow, Indirect Tensile Strength (ITS), resilient modulus, and dynamic creep provide valuable insights into the strength, stiffness, cracking resistance, and deformation behaviour of bituminous mixes [22], [23].

Methodology

The experimental program was designed to compare the performance of Bituminous Concrete (BC-2) mixes prepared using VG-40 and Polymer Modified Bitumen RG 70-10E. Aggregates were procured from the CSIR-CRRI campus and graded as per BC-2 requirements in accordance with MoRTH specifications [18]. The physical properties of aggregates, including specific gravity, water absorption, impact value, abrasion value, and flakiness–elongation index, were determined following IS 2386 (Parts I–IV) [24], ensuring their suitability for bituminous paving applications.
Binder characterization was carried out for both VG-40 and PMB RG 70-10E using penetration [25], softening point [26], ductility [27], elastic recovery [19], and specific gravity tests [28], in accordance with IS-73:2018 [29] and IS-15462:2019 [19]. These tests provided baseline information on consistency, stiffness, elasticity, and temperature susceptibility of the binders.
Marshall mix design was conducted following ASTM D6927 [21]. Trial specimens were prepared with bitumen contents ranging from 4.5 % to 6.5 % [Fig. 1], and parameters such as Marshall stability, flow, air voids, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were determined. The optimum bitumen content (OBC) was selected based on 4 % air voids and MoRTH requirements, resulting in 5.4 % for VG-40 and 5.6 % for PMB mixes.

Figure 1 Sample for Mix Design

Performance evaluation was carried out on specimens prepared at their respective OBC values. Marshall Stability and Flow tests [Fig. 2] were performed at 60°C. Indirect Tensile Strength (ITS) tests [Fig. 3] under dry and wet conditions were conducted in accordance with AASHTO T283 [22]. The resilient modulus [Fig. 4] was measured at 35°C using repeated haversine loading as per ASTM D4123 [30], while dynamic creep tests [Fig. 5] were conducted at 40°C to evaluate permanent deformation characteristics

Figure 3 Marshall Stability & Flow Test

Figure 3 ITS Test

Figure 4 Resilient of Modulus Test

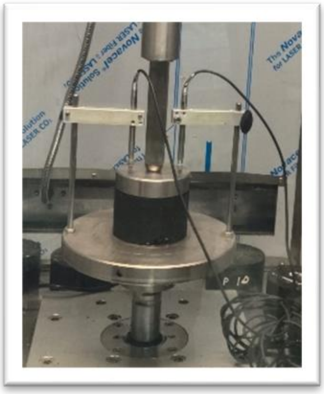


Figure 5 Dynamic Creep Test

Results and Discussion

Aggregate Properties

The physical and mechanical properties of the aggregates used in the study are presented in Table 1. Both coarse and fine aggregates fully satisfied the requirements specified by **MoRTH**, confirming their suitability for Bituminous Concrete (BC-2) mixes.

Table 1: Properties of Aggregate

Sl. No.	Tests	Result	Requirements as per MoRTH
1	Specific Gravity 1.Coarse aggregate 2.Fine aggregate	 2.53 2.67	 2.5 – 3.2
2	Water Absorption Test, (%)	0.75	2 Max
3	Aggregate Impact Test, (%)	19	24 Max
4	Los Angeles Abrasion Test, (%)	28	30 Max

5	Aggregate Crushing Value Test (%)	27	30 Mini
6	Combined Flakiness and Elongation Index (%)	30	35 Max
7	Stripping Value (%)	96	95

The specific gravity values (2.53 for coarse aggregate and 2.67 for fine aggregate) indicate dense aggregates with good load-bearing capacity. Water absorption was limited to **0.75%**, significantly lower than the permissible maximum of 2%, indicating low porosity and reduced moisture susceptibility.
Aggregate impact value (19%), Los Angeles abrasion value (28%), and crushing value (27%) were all well within the specified limits, demonstrating adequate resistance to impact, abrasion, and compressive stresses under traffic loading. The combined flakiness and elongation index of **30%** suggests favourable aggregate shape characteristics, which enhance interlocking and load transfer within the mix.
A high stripping value of **96%** confirms excellent binder–aggregate adhesion, ensuring improved resistance to moisture-induced damage. Overall, the aggregate properties were appropriate for producing durable and stable BC-2 mixtures.

Binder Properties

The physical properties of VG-40 and PMB (SBS-modified) binders are summarized in **Table 2**. PMB exhibited a lower penetration value (51) compared to VG-40 (60), indicating higher stiffness resulting from polymer modification. The softening point of PMB (65 °C) was substantially higher than that of VG-40 (50 °C), reflecting superior resistance to softening at elevated temperatures.
Both binders satisfied ductility and elastic recovery requirements; however, PMB demonstrated enhanced elastic response due to the presence of SBS polymer. These results confirm that polymer modification improves high-temperature performance and elastic recovery without adversely affecting binder workability.

Table 2: Properties of Binder

Properties	VG-40	PMB (SBS)
Specific Gravity	1.02	1.03
Penetration Test on 25^0 C	60	51
Ductility Test at 27^0 C	79	75
Elastic Recovery Test at 27^0 C	70	70
Softening Point Test,	50	65

Marshall mix Design and Optimum Binder Content

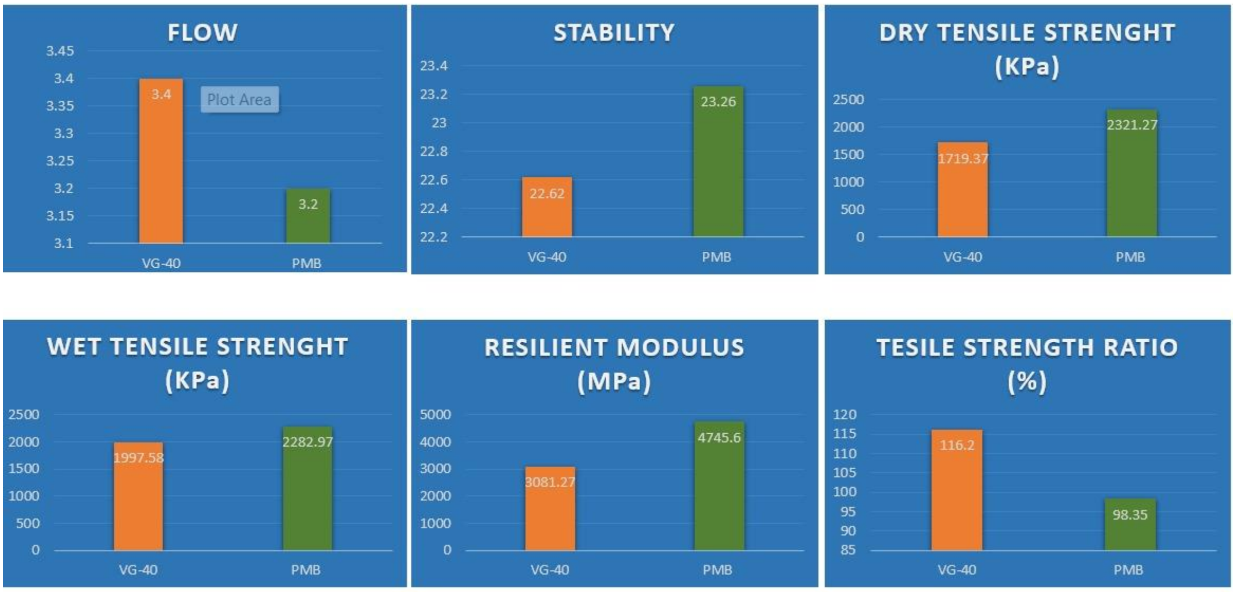
Marshall mix design results for VG-40 and PMB mixes are presented in **Table 3**. For both binders, stability increased with binder content up to an optimum level and decreased thereafter, exhibiting typical Marshall behaviour.
At corresponding binder contents, PMB mixes consistently achieved higher stability values than VG-40 mixes, indicating improved load-carrying capacity. Flow values for PMB were generally lower, suggesting enhanced resistance to plastic deformation while maintaining acceptable flexibility.
The optimum binder content (OBC), determined based on **4% air voids** and MoRTH criteria, was found to be **5.4% for VG-40** and **5.6% for PMB**. The slightly higher OBC for PMB is attributed to its higher

viscosity and polymer network structure. Despite this increase, PMB mixes exhibited superior volumetric and mechanical performance.
The Marshall stability and flow values using OBC showed that PMB mixer achieved higher average stability (**23.26 kN**) at 5.6 binder content as compared to VG-40 mixes (**22.62 kN**) where binder content was 5.4, indicating better resistance to applied loads. Flow values for both mixes were identical (**3.4 mm**) and within permissible limits.

Table 3: Result of Mix Design

Binder Type	Binder Content (%)	Stability (kN)	Flow (mm)	Bulk Density (g/cc)	Air Voids (Vv %)	V_{MA} (%)	V_{FB} (%)
VG-40	4.5	9.2	2.3	2.362	5.6	15.8	64.6
	5.0	10.6	2.8	2.372	4.8	15.7	69.4
	5.4 (OBC)	**22.62**					
	5.5	11.4	3.3	2.377	4.1	15.6	73.7
	6.0	10.9	3.9	2.375	3.5	15.4	77.3
	6.5	9.7	4.5	2.369	3.1	15.3	79.7
PMB RG 70-10E	4.5	10.8	2.0	2.374	5.3	15.9	66.7
	5.0	12.2	2.5	2.382	4.6	15.8	71.2
	5.5	13.5	2.9	2.386	4.0	15.6	74.5
	5.6 (OBC)	**23.26**					
	6.0	13.1	3.4	2.383	3.6	15.5	76.8
	6.5	12.2	3.8	2.380	3.3	15.4	78.8

Mechanical Performance



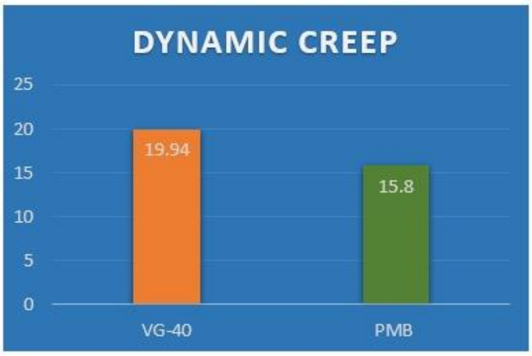


Figure 6 Comparison of mechanical properties between VG-40 and PMB

Results of dry and wet tensile strength shows 2321.27 and 2282.97 KPa respectively for the case of PMB as compared to VG-40 as shown in **fig.6**. Resilient Modulus value showed 4745.6 MPa of PMB as compared to 3081.27 MPa for the case of VG-40. It is interesting to note from fig.6 showing the lower value in case of dynamic creep having 15.80 for the case of PMB indicating enhanced resistant to permanent deformation under repeated loading.

Conclusion

The experimental investigation confirms that SBS polymer–modified binder (PMB) significantly enhances the performance of BC-2 mixes compared to conventional VG-40 binder. All aggregates satisfied MoRTH requirements, ensuring a reliable base for performance evaluation. PMB exhibited superior binder characteristics, including higher stiffness and softening point, resulting in improved high-temperature stability and elastic response.

Marshall mix design results showed higher stability and comparable flow for PMB mixes at optimum binder content, indicating improved load-bearing capacity without compromising flexibility. PMB mixes demonstrated markedly higher indirect tensile strength, resilient modulus, and moisture resistance, along with better resistance to permanent deformation under dynamic creep loading.

Although PMB required a marginally higher binder content, the overall improvement in mechanical performance and durability clearly outweighs this increase. The findings highlight the suitability of PMB-modified BC-2 mixes for heavily trafficked pavements subjected to high temperatures and moisture-prone conditions, particularly under Indian climatic and traffic scenarios.

Dry and wet ITS, resilient modulus, and dynamic creep results (Fig. 6) demonstrate the superior performance of PMB, with higher tensile strengths (2321.27 and 2282.97 kPa), significantly greater resilient modulus (4745.6 MPa), and lower dynamic creep value (15.80 Pa) compared to VG-40, indicating enhanced resistance to permanent deformation under repeated loading.

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