Life Cycle Cost Analysis of Flexible Pavements with Modified Asphalt Mixes – Indian Experience

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ABSTRACT: Rutting in asphalt pavement layers is a combination of densification and shear deformation. Increasing traffic and environmental variations reduce the shear resistance of the asphalt mixes. Proper use of polymers, as well as recycled waste materials can lead to improvement of the properties of asphalt mixes. Use of recycled materials in pavement construction can lead to significant reduction disposal processes. In this comprehensive study, the performance of Styrene Butadiene Styrene (SBS) polymer, crumb rubber, natural rubber and waste plastic modified asphalt binder mixes to permanent deformation has been evaluated using dry wheel tracker and compared with the performance of unmodified asphalt binder mix. Data from the physical and mechanical characterization of binders and mixes was used in Mechanistic-Empirical Pavement Design Software (MEPDS) to evaluate the comparative performance for a specific site conditions. Effects of overloading and axle configuration were keenly considered in the analysis. Life cycle cost analysis (LCCA) was carried out to evaluate the advantages of modified asphalt binders over unmodified binders. It was observed from results that polymer modified asphalt binder mixes show better performance with high service life and low life cycle cost when compared to mixes with all other asphalt binders used in this study.

KEYWORDS*:* Asphalt mix, modifiers, rutting, performance, service life.

1 INTRODUCTION

Permanent deformation or rutting in flexible pavements is a major distress mode and usually occurs as a result of a combination of densification and shear flow. It may be caused by the action of high stress at high temperatures on the surface of the pavement. With an extensive road network of 3.3 million kilometers, India has the second largest road network in the world. Indian roads carry about 61% of the freight and 85% of the passenger traffic. The pavements are observed to pre-maturely fail primarily due to inappropriate selection and use of pavement materials regardless of the climatic conditions and type, magnitude and volume of traffic loading. This results in costly rehabilitation and reconstruction. Judicious selection of construction materials in pavement construction may solve this problem. In this regard modified binders in asphalt layers have gained importance around the world. These modified binders are reported to be performing satisfactorily at high traffic load levels and hence there is a need to study the relative performance of bituminous mixes with different modified asphalt binders under heavy axle loads and tropical temperatures that are prevalent in India.

2 OBJECTIVES

The objectives of the present study are to (1) characterize the rutting resistance of asphalt mixes with different types of modified and unmodified asphalt binders and (2) evaluate the effect of asphalt type on the pavement performance using mechanistic-empirical design software with different climatic and loading conditions. (3) predict the performance of asphalt mixes with modified and unmodified binders (4) compare the life cycle cost of flexible pavements with modified asphalt mixes with unmodified asphalt mixes.

3 BACKGROUND

Rutting is the manifestation of permanent deformation in different layers of the pavement. The asphalt layer significant contributes to the permanent deformation in hot climatic conditions (Palit et al. 2004). The type of modifier used in the asphalt layers will significantly affect the permanent deformation characteristics of asphalt mixes (Tayfur et al. 2007). Temperature has more significant effect on the modulus of mixes than the asphalt grade, content and air voids (Tarefder et al. 2007). Mixes with SBS polymer modified binder have been reported to be more rut resistant when compared to mixes with unmodified binder. Wong et al. (2004) showed that generalized dynamic shear modulus can be used as a stiffness indicator to rank the rutting resistance of unmodified and modified asphalt mixtures. Rutting occurred as a combination of densification and shoving in the unmodified mixtures, whereas in polymer modified mixtures it was only densification that contributes to rutting (Sirin et al. 2008). Liu et al. (2009) reported that crumb rubber content has the significant effect on the mechanical properties of asphalt mixes followed by the effect of type and size of rubber particles. Mechanical properties of binder and in-turn of the mix could be improved by modification (Ching and Wing-gun, 2007). Using waste plastics in asphalt mixes as a modifier not only improves the binder properties but also helps to solve the problem of disposal of waste plastics (Sridhar et al. 2005). Srivastava and Baumgardner, 1996 showed that the overlay thickness could be reduced by 50 % and also cost saving of 15 to 25 % can be achieved by using modified asphalt binders.

The above studies have clearly shown the advantage of modified asphalt binders in pavement construction. However with the increasing number of additive types and recycled materials there is need to study the relative performance of these modified binders duly considering the traffic loading and tropical climatic conditions that are prevalent in India. Moreover a cost analysis with consideration of the importance of pavement performance will clearly demonstrate the feasibility of modification.

4 LABORATORY INVESTIGATIONS

4.1 Materials Used

Four different types of modified asphalt binders namely Styrene Butadiene Styrene (SBS) Polymer Modified Binder (PMB), Crumb Rubber Modified Binder (CRMB), Natural Rubber Modified Binder (NRMB) and Waste Plastic Modified Binder (WPMB) were used along with a control binder viz., unmodified asphalt binder (Viscosity Grade, VG-30). The aggregate gradation (Figure 1) selected in this study is the one which is recommended by Ministry of

Road Transport and Highways (MORT&H) for high density corridors. The properties of the asphalt binders are presented later in this paper (Table 1).

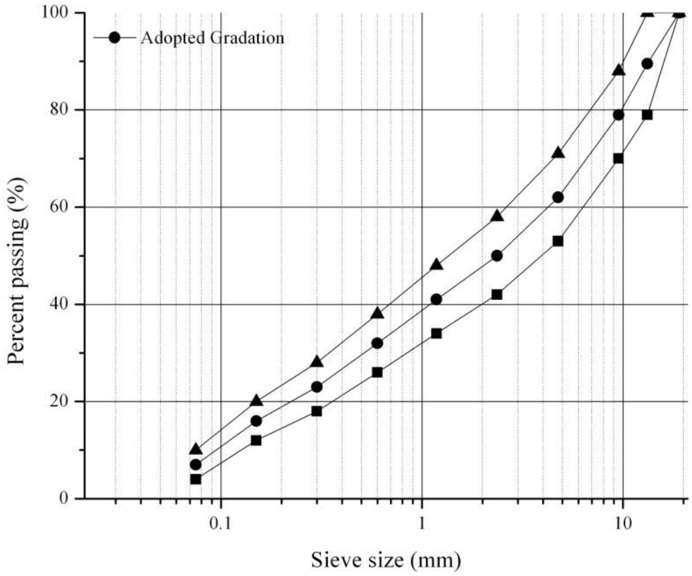

Figure 1: Midpoint gradation adopted (MORT&H, 2001)

4.2 Parametric Consideration

In order to study the effect of asphalt binder modification on the rutting performance of mixes, an asphalt binder content of 5.25 % was adopted for all the asphalt binders for a single aggregate gradation. The compaction level of 160 gyrations was maintained constant using Superpave gyratory compactor.

4.3 Wheel Tracker

An European standard dry wheel tracker was used to evaluate the rutting potential of asphalt mixes. A load of 700 N was applied through a rubber hosed wheel of 200 mm diameter, 50 mm width on 150 mm diameter cylindrical samples. The speed was maintained at 53 passes per minute. The asphalt mixes were conditioned for 6 hours before the commencement of the test in an environmental chamber. All the mixes were tested at different temperatures from 30 to 60 ^{o}C for 10,000 passes or up-to a rut depth of 10 mm, whichever is earlier.

4.4 Mechanistic-Empirical Pavement Design Guide (M-E PDG) and Software (ME-PDS)

ME-PDG provides the pavement community the state-of-the-practice tool for the design of new and rehabilitated pavement structures (NCHRP, 2004). Specific site conditions and material properties can be incorporated for analyzing the pavement performance. Performance predictions are based on the mechanistic-empirical principles. The approach makes it possible to ensure that specific distress types are not likely to develop.

This study focuses on the comparison of rutting performance of asphalt mixes with modified asphalt binders with unmodified asphalt binders in the bituminous wearing courses. Even though M-E PDG was never calibrated for modified asphalt mixes, other than conventional mix, in the absence of any other more comprehensive materials-structural design system, an attempt has been made to use it for relative performance evaluation. However the assumption is that the properties of modified asphalt binder could also be reflected through the PG grade, which is considered in the M-E PDG.

The pavement structure is composed of 50 mm thick asphalt concrete, 150 mm crushed stone base, 150 mm crushed gravel sub-base and 500 mm thick prepared subgrade soil of A-1 type. The pavement structure was designed for an annual average daily traffic of 5000 vehicles, out of which 56 % of trucks were considered for a design life of 20 years. The analysis was carried out using the Mechanistic – empirical pavement design software. The climatic data of Miami in Florida and Las Vegas in Nevada which have similar climatic conditions as most of the Indian cities were considered. Standard single axle (class 5, 56 %) and multi axle trucks (class 9, 74 %) were considered to study the effect of axle configuration on the performance of the flexible pavement considered in the present investigation.

4.5 Life cycle cost analysis (LCCA)

Life Cycle Cost Analysis (LCCA) is an indispensable technique that employs well-established principles of economic analyses to evaluate long-term performance of competing investment options (Kaan et al. 2003). It enables decision makers to optimize the expenditure of available funds to provide an economic assessment of competing design or rehabilitation strategies.

For the present work, LCCA was carried out considering different modified asphalt binders in the wearing course. The agency cost viz., construction cost, routine maintenance cost, rehabilitation cost and the salvage cost were considered in the analysis. Lane width of 7 m and length of 5 km was considered to estimate the total cost. The road user cost was not considered. All the costs were discounted to the present year at a rate of 6 %.

5 RESULTS AND DISCUSSIONS

5.1 Laboratory material characterization

It can be seen from Table 1 both unmodified and modified asphalt binders satisfies the specified requirements (IS: 73-2006 & IRC: SP-53, 2002). Modification to base asphalt with various additives (polymer, rubber, crumb rubber and waste plastic) has improved the rutting resistance ($G^*/\sin\delta$) of asphalt binders when compared unmodified asphalt binder (VG-30). However, WPMB failed to satisfy the elastic recovery requirements on both un-aged and short term aged conditions. Form this it may be concluded that the use of waste plastic as modifier increases the stiffness but, in-turn fails to enhance the elastic properties. Apparent viscosity of un-aged PMB was higher than the specified which may be due to higher concentration of polymer.

No significant difference in the volumetric properties of asphalt mixes with different asphalt binders were found (Table 2) since the parameters like aggregate gradation, binder content and compactive effort were maintained constant. However mixes with NRMB has higher void content when compared to mixes with other asphalt binders.

Table 1: Results of the tests carried out on the modified and unmodified asphalt binders

PROPERTIES	VG – 30	CRMB	PMB	NRMB	WPMB
Penetration at 25 °C 0.1mm, 100gm, 5sec	60 to70 (60 to 70)	50 to 60 (50 to 90)	30 to 40 (< 60)	50 to 60 (50 to 90)	30 to 40 (30 to 50)
Softening point (R&B), °C	46 (45-55)	60 (55 min)	56 (55 min)	50 (50 min)	62 (60 min)
Flash Point, °C	> 220 (175 min)	> 220 (220 min)	> 220 (220 min)	> 220 (220 min)	220 (220 min)
Ductility at 27 °C cm	80 (75 min)	100 +	57.7	78.5	34
Specific gravity, gm/cc	1 (0.99 min)	1.03	1.03	1	1.045
Elastic recovery at 15°C (%)	71	77 (70 min)	68 (50 min)	55 (40 min)	23.67 (50 min)
Viscosity at 150°C, Poise	5.29 (3 min) @ 135°C	*7.29* (2-6)	*7.87* (2-6)	2.97 (2-6)	5.33 (3-9)
Test results on thin film oven test residue					
Loss in weight (%)	0.42 (1 max)	0.19 (1 max)	0.35 (1 max)	0.3 (1 max)	*1.01* (1 max)
Reduction in penetration of residue at 25 °C (%)	18.23 (48 max)	12.72 (35 max)	28.57 (40 max)	11.67 (40 max)	26.67 (35 max)
Increase in softening Point, °C	4	2 (6 max)	4 (6 max)	3 (6 max)	*7* (6 max)
Elastic recovery at 25 °C (%)	--	60 (50 min)	48 (35 min)	32 (25 min)	*23* (35 min)
Equivalent performance grade	58-10	76-10	82-10	64-10	70-10

Table 2: Volumetric properties of mixes with unmodified and modified asphalt binders

Asphalt binder types	Air voids, %			VMA, %	VFB, %
	N (samples)	μ (mean)	σ (Std dev)		
VG-30	12	3.78	0.48	14.19	73.36
CRMB	12	4.14	0.33	14.44	71.34
PMB	12	4.05	0.43	14.39	71.88
NRMB	12	4.23	0.42	14.06	69.90
WPMB	12	4.19	0.32	14.46	70.97

5.2 Laboratory Characterization of Rutting

Rutting resistance of mixes with modified and unmodified asphalt binders were evaluated using dry wheel tracker at varying temperatures. Figure 2 shows the variation in rut depth at various temperatures for mixes with different modified and unmodified asphalt binders. The rut depths of the mixes with modified asphalt binders were relatively lower when compared to the mix with unmodified asphalt binder. The rutting resistance of the mixes was found to be significantly affected by the temperature. Significant difference in rutting resistance of asphalt mixes was observed at high temperature of 60 ^{o}C. Asphalt concrete mixes with polymer modified asphalt binder showed highest resistance to rutting at 60 ^{o}C while mixes with unmodified asphalt binder showed the least. It can also be observed from Figure 2 that mixes with polymer modified asphalt binder were least sensitive to increase in temperature. Mixes with natural rubber modified and unmodified asphalt binders were found to be more sensitive to variations in temperature. No significant difference in rutting resistance was observed at low temperatures of 30^{o}C to 40 ^{o}C among different asphalt binders used in the study. The results further imply that mixes with modified asphalt binders can withstand higher strain levels when compared to mixes with unmodified asphalt binder.

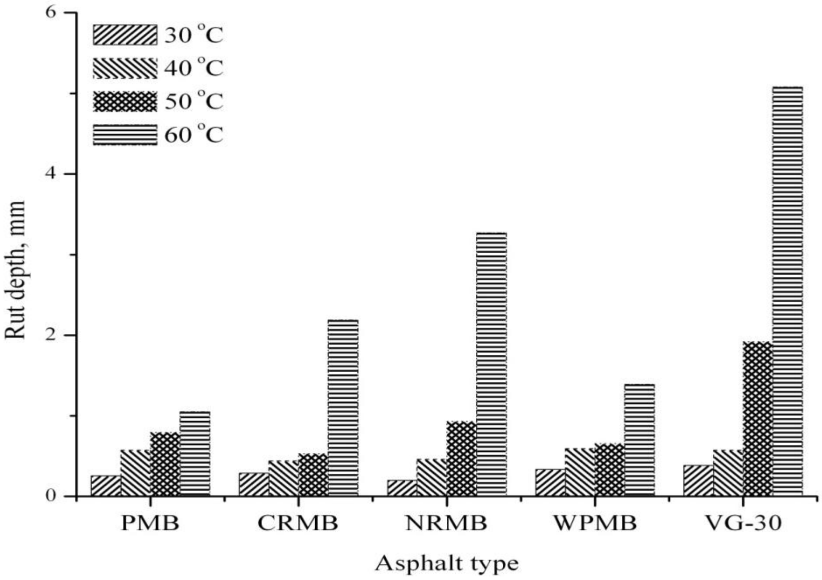

Figure 2: Laboratory rutting resistance of asphalt mixes with varying asphalt type and temperature after 10,000 repetitions

6 PAVEMENT PERFORMANCE

6.1 Effect of Binder Type on Rutting Performance

From Table 3 it can be seen that polymer modified asphalt mix offers high resistance to rutting, which extends the pavement life (20 mm total rut depth) to 12 years. The rutting in polymer modified asphalt mix is 50 % lower than the rutting in the mix containing unmodified asphalt binder. It can be seen that the asphalt mixes with modified asphalt binders offer longer predicted life than the mix with unmodified asphalt binder. The asphalt mixes with modified asphalt binder has higher life of 6 years when compared to the unmodified asphalt binder mix.

It can be observed from Table 3 that the temperature has a significant effect on the rutting behavior of the asphalt mixes and hence the service life of pavement structure. The computed values of rutting for Nevada climatic conditions (59 ^{o}C) are found to be higher than Florida

(53 ^{o}C). This clearly shows the effect of temperature on the rutting resistance of asphalt mixes is significant. The polymer modified asphalt mixes showed highest resistance to rutting at high temperatures. The service life of the pavement structure with polymer modified asphalt binder in the wearing course increases by 2 and 3 times when compared to unmodified asphalt binder at 53 and 59 ^{o}C respectively. It can also be observed that reduction in pavement service life due to increase in temperature was minimal in pavement structure with polymer modified asphalt binder in the wearing course. When compared to a pavement structure with unmodified asphalt binder in the wearing course, all modified asphalt binders offered higher resistance to rutting.

Table 3: Reduction in pavement life with variation in pavement temperature (as predicted by ME-PDS)

Asphalt Type	Pavement life, years		Reduction in life with increase in pavement temperature, %
	Pavement temperature, ^{o}C		
	53	59	
VG-30	5.75	2.25	61
NRMB	7.58	3.58	53
WPMB	8.83	4.75	46
CRMB	10.5	5.83	44
PMB	11.83	6.92	42

6.2 Effect of Axle Configuration on Pavement Performance

The rut depths values for two axle configuration were studied viz., class 5 and class 9 (of the AADT of 5000 per day, 56 % of class 5 and 74 % of class 9). Figure 3 and 4 shows the performance of unmodified and modified asphalt binder mixes for class (5) and class (9) type vehicles respectively. If class (9) trucks form the predominant (74 %) composition in the traffic, the pavement service life is found to reduce by 40 % when compared to class (5) as the predominant (56 %) composition. Pavements with wearing course of polymer and crumb rubber modified asphalt binder mixes offered highest resistance to traffic loading when compared to pavements with wearing course of asphalt mixes with other binder types. Waste plastic modified and natural rubber modified asphalt mixes offered higher service life when compared to unmodified asphalt binder mix. Use of asphalt concrete mixes with polymer modified binders is recommended for highways trafficked by heavier vehicles.

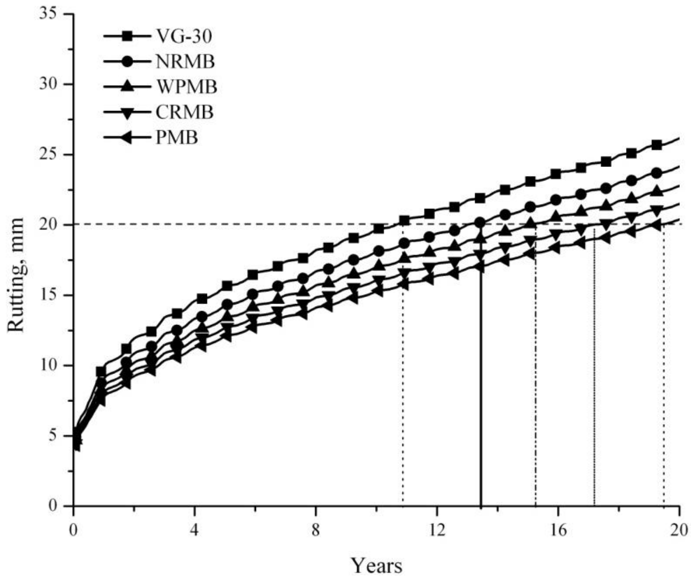

Figure 3: Variation of rut depth with varying binder types for Class (5) truck

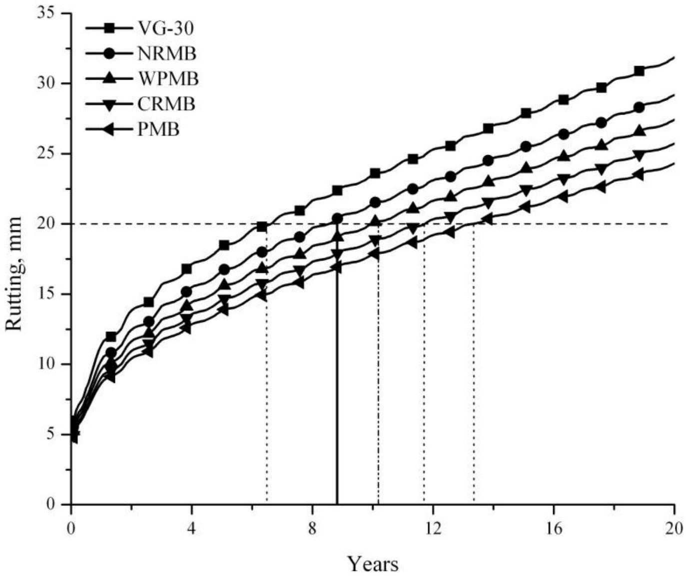

Figure 4: Variation of rut depth with varying binder types for class (9) truck

7 ECONOMICS

Net Present Value (NPV) is the gross value of the net benefits discounted to the base year. Salvage Value (SV) represents the value of an investment alternative at the end of the analysis period. NPV and SV were calculated using the below relations (Walls and Smith, 1998).

$$NPV = Initial\ cost + \sum_{k=1}^{n} Rehabilitaion\ cost_k \left[\frac{1}{(1+i)^{nk}}\right] \quad (1)$$

where: i = discount rate

n = year of expenditure

$$SV = \left(1 - \frac{L_A}{L_E}\right) C \quad (2)$$

where: L_E = is the expected life of rehabilitation alternative

L_A = portion the expected life consumed
C = cost of the rehabilitation strategy

Table 4 Net present values using deterministic approach for different alternatives

Alternatives (Binder Type)	Agency cost, USD,$					Ratio of costs, (UM/M)
	Construction cost,	Routine Maintenance cost	Rehabilitation cost	Salvage value	Total costs	
VG-30	532,589	8,159	340,756	532,570	857,733	
NRMB	542,715	8,269	303,272	162,810	785,945	1.09
WPMB	542,715	8,269	286,105	135,675	784,863	1.09
CRMB	542,715	8,509	254,626	814,050	781,070	1.10
PMB	552,840	8,837	140,890	552,820	689,303	1.24

* UM = Unmodified asphalt binder, M = Modified asphalt binder

From Table 4 it can be seen that asphalt mixes with polymer modified asphalt binders offer higher benefits when compared to other alternatives considered in this study. However compared to alternative with unmodified asphalt binder, all other alternatives with modified asphalt binders were found to be economical. The life cycle costs of mixes with other modified asphalt binders were found to be comparable with that of mix with unmodified asphalt binder.

8 CONCLUSIONS

1) Rutting resistance of asphalt concrete mixes with unmodified asphalt binder was found to be more susceptible to temperature when compared to mixes with modified asphalt binders.
2) A SBS polymer modified asphalt binder mix was found to offer 4.8 times the resistance of that offered by an unmodified binder mix during laboratory rutting studies.
3) Use of polymer modified asphalt binder enhanced the pavement service life (resistance to rutting) twice when compared to unmodified asphalt binder under the conditions considered in this study.
4) Increase of 6^{o}C (53 to 56^{o}C) in pavement temperature results in a 50 % reduction of the pavement rutting resistance.
5) A higher composition (74 %) of multi axle trucks reduces the rutting resistance of pavement structure by 40 %.
6) Utilization of waste plastic and other modified asphalt reduced the life cycle cost of pavement when compared to unmodified asphalt binder. However pavement with SBS polymer modified asphalt binder resulted in lowest life cycle cost among the alternatives considered in this study.

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