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Laboratory Investigation of Fatigue Performance of DBM-II Mixes Incorporating RAP Using Unmodified and Modified Bitumen

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Abstract
This study evaluates the mechanical performance of Dense Bituminous Macadam (DBM-II) mixes incorporating reclaimed asphalt pavement (RAP) and different filler materials using VG-40 and PMB-40 binders. A total of 24 mix combinations were prepared by varying RAP content (0–30%) and filler type (stone dust, fly ash, and GGBS). Marshall stability tests were conducted to determine optimum binder content, while indirect tensile strength (ITS), indirect tensile fatigue test (ITFT), and resilient modulus (M_R) assessments were carried out to evaluate durability and deformation characteristics. Results showed that all mixes satisfied MoRTH specifications, confirming their structural adequacy. PMB-40 binder consistently enhanced stability, tensile strength, and durability compared to VG-40, while GGBS emerged as the most effective filler, followed by stone dust and fly ash. The resilient modulus increased with RAP incorporation due to aged binder stiffness, though fatigue life decreased with higher RAP content. Overall, PMB-40 mixes with GGBS filler exhibited the most balanced performance, ensuring superior stability, stiffness, and crack resistance, thereby establishing their suitability for sustainable DBM-II pavement applications.

Keywords: Reclaimed Asphalt Pavement, Dense Bituminous macadam, Marshall Stability

1. Introduction
Fatigue damage is one of the primary distresses in bituminous concrete pavements, developing under the action of repeated axle loads that generate cyclic tensile and compressive strains within the asphalt layers. Typically, tensile strains occur at the bottom of the bituminous layer while compressive strains are concentrated at the top (Sudarsanan, 2022). With time, these repeated strain reversals initiate cracking patterns such as longitudinal, hexagonal, and alligator cracks, which intensify when fragments begin to dislodge in wheel paths (Ghuzlan and Carpenter, 2006; Suh et al., 2010). The capacity of an asphalt mixture to withstand such repeated load applications without structural fracture is defined as its fatigue life or fatigue resistance. Fatigue cracking is commonly categorized as bottom-up and top-down, where bottom-up fatigue initiates at the underside of the asphalt concrete layer due to tensile strains and propagates upward to the surface, often aggravated by environmental influences such as temperature fluctuations and moisture infiltration (Mackiewicz, 2013). Consequently, fatigue is recognized as a major determinant of pavement performance, with cyclic traffic loading and environmental stresses leading to progressive degradation and surface cracking (Taher M. Ahmed et al., 2019). Given that

bituminous mixtures are viscoelastic and anisotropic materials, their response is highly dependent on temperature, loading frequency, and stress conditions, which directly influence their fatigue behavior (Cheng et al., 2022). Accordingly, the mode of loading and test conditions significantly affect fatigue performance (Kim et al., 2002; Xiao et al., 2022).

In general, stiffness tests quantify horizontal deformation, while fatigue tests capture vertical deformation; however, the Indirect Tensile Fatigue Test (ITFT) is characterized by stress non-uniformity, as tensile stresses concentrate at the specimen's center (Hudson and Kennedy, 1968). When conducted under controlled stress mode with haversine loading, ITFT often induces both fatigue cracking and permanent deformation, particularly under elevated temperature conditions (Brown, 1995; Di Benedetto et al., 2004; Cocurullo et al., 2008; Maggiore et al., 2012; Johnson, 2010). The resilient modulus (M_R) of bituminous mixes, which can be evaluated through fatigue tests, is defined as the ratio of the applied cyclic stress to the recoverable (elastic) strain of the material under repeated loading. As per IRC:37-2018, the resilient modulus of bituminous mixes is influenced by factors such as binder grade, frequency or load application time, air void content, aggregate shape, aggregate gradation, maximum aggregate size, and bitumen content, while in mixes prepared with modified binders, the modulus value varies widely depending on the type of modifier, blending duration, quantity of admixtures, and the extent of air blowing of the base bitumen

2. Methodology

2.1 General:

For this study, Dense Bituminous Macadam (DBM-II) mixes were prepared using two types of binders, namely VG-40 and PMB-40. Although both binders exhibit comparable penetration values, they differ in chemical composition, with PMB-40 being a polymer modified binder and VG-40 a conventional viscosity grade binder. Table 1 represents the characterization of both binders. The Marshall Stability test was conducted to determine the optimum binder content (OBC) for each mix. Subsequently, Reclaimed Asphalt Pavement (RAP) was incorporated into the mix at varying proportions of 10%, 20%, and 30%, replacing the virgin aggregates. To evaluate the influence of filler type on mix performance, three different fillers were considered: stone dust, fly ash, and ground granulated blast furnace slag (GGBS).Different mix combinations are listed in Table 2. The Indirect Tensile Strength (ITS) test was conducted to evaluate the maximum tensile stress that the bituminous mix could withstand under diametric loading. Following this, the Indirect Tensile Fatigue Test (ITFT) was performed to assess the fatigue performance of the mixes. From the ITFT results, the resilient modulus (MR) was determined as the ratio of applied cyclic stress to recoverable strain, while the fatigue life (Nf) was established as the number of load repetitions the mix could sustain before failure.

Table 1: Physical properties of VG-40 and PMB-40 Bitumen

Sl no.	**Characteristics**	**VG-40**	**PMB-40**	**Requirements as per Table-1, IS 73:2013**	**Requirements as per Table-2, IS 15462: 2004**
				VG40	PMB-40
1	**Penetration at 25°C, 100 g, 5 s, 0.1 mm, Min**	37	43	35	30-50

2	**Flash point (Cleveland open cup), °C, Min**	272	312	220	220
3	**Solubility in trichloroethylene, percent, Min**	99.22	99.15	99.0	---
4	**Softening point (R&B), °C, Min**	52	64	50	60
5	**Specific Gravity**	0.98	1.04	---	---
6	**Absolute viscosity at 60°C, Poises**	4105	---	3200- 4800	---
7	**Viscosity @150°C, Poise**	---	4.59	---	3-9

2.2 Determination of Resilient Modulus (M_R) and Fatigue life (N_f) of Dense Bituminous Mix :

The test method adopted for this study follows ASTM D4123**.** Cylindrical specimens with a diameter of 101.6 mm and height of 63.5 mm were prepared using Marshall compaction. Prior to testing, the specimens were conditioned in a temperature-controlled oven at 35 °C for a minimum of 4 hours to ensure uniform thermal equilibrium. Each specimen was mounted horizontally between the loading platens of the testing frame such that the load was applied along the vertical diameter**.** To measure the horizontal recoverable strain at the specimen's center, a transverse deformation device (LVDTs or circumferential extensometer) was attached across the horizontal diameter (Figure 1). A haversine load waveform with 0.1 s load pulse and 0.9 s rest period was applied, corresponding to an effective frequency of 1 Hz**.** Loading was continued until a stable strain response was achieved, with a minimum of 50 cycles recommended; however, in this study, 200 cycles were adopted for resilient modulus evaluation. At the end of 200 cycles, the horizontal deformation was recorded, and the resilient modulus (M_R) and initial tensile strain (ε_t) were calculated using Equations (1) and (2), respectively. For fatigue life (N_f) determination, cyclic loading was continued until specimen failure, defined as the point at which the specimen fractured or exhibited a sharp reduction in load-carrying capacity. The number of cycles at failure was recorded as the fatigue life of the bituminous mix.

Resilient Modulus, $M_R = \frac{P \text{ x } (0.27+\mu)}{HR \text{ x } t}$ (1)

Where, M_R = Resilient Modulus, MPa, H_R = Resilient Horizontal Deformation, P = applied repeated load, N, μ is Poisson's ratio (0.35), t=thickness of specimen, mm

Initial tensile strain, $\epsilon_t = \frac{\sigma x \ (1+3\mu)}{MR}$ (2)

Where, ϵ_t= Initial tensile strain, σ_x= Tensile Stress, MPa

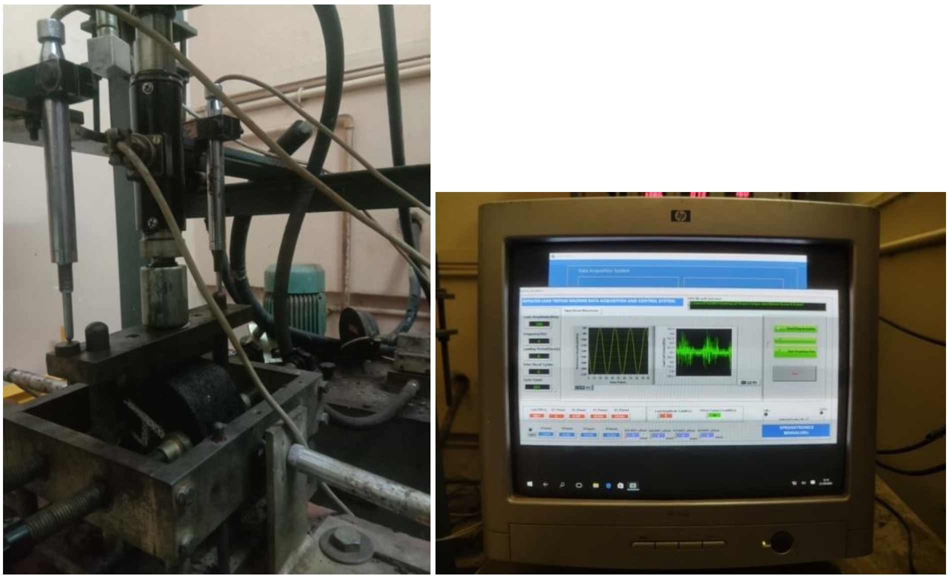

Figure 1: Indirect tensile Fatigue test setup

Table 2: Nomenclature of mix considered for study

Sl. No.	Bitumen type	Filler Type	RAP Content (%)	Type of Mix	Nomenclature
1	VG-40	Stone Dust	0	QSTM	QSTM - 1
2			10		QSTM – 2
3			20		QSTM – 3
4			30		QSTM - 4
5		Fly Ash	0	QFTM	QFTM -1
6			10		QFTM – 2
7			20		QFTM – 3
8			30		QFTM – 4
9		GGBS	0	QGTM	QGTM - 1
10			10		QGTM – 2
11			20		QGTM – 3
12			30		QGTM – 4
13	PMB-40	Stone Dust	0	RSTM	RSTM-1
14			10		RSTM-2
15			20		RSTM-3
16			30		RSTM-4
17		Fly Ash	0	RFTM	RFTM-1
18			10		RFTM-2
19			20		RFTM-3
20			30		RFTM-4
21		GGBS	0	RGTM	RGTM-1
22			10		RGTM-2
23			20		RGTM-3
24			30		RGTM-4

3. Results and Discussion

3.1 Marshall Stability Test

According to MoRTH specifications for DBM-II mixes, the minimum Marshall stability requirement is 900 kg. The test results clearly indicate that all the prepared mixes, both with VG-40 (Q-series) and PMB-40 (R-series), comfortably satisfy this criterion, as stability values ranged from 1178 kg (QSTM-4) to 1920 kg (RGTM-1). This confirms that all the mixes are structurally adequate for use in DBM-II layers. Furthermore, the use of PMB-40 binder consistently enhanced stability values compared to VG-40 mixes, while GGBS emerged as the most effective filler, followed by stone dust and fly ash. Therefore, all the trial mixes not only meet but exceed the MoRTH requirements, ensuring suitability for heavy-duty pavement applications. RAP incorporation up to 30% has not affected the marshal stability of mix (Figure 2).

The flow values for all mixes increased with RAP content due to stiffness of binder on RAP incorporation. The Q-series mixes showed flow values in the range of 3.2–3.9 mm, while the R-series mixes recorded slightly higher flows of 3.2–4.1 mm. Although the R-series exhibited marginally greater deformation, the flow values for both binder types remained within the acceptable range (2-4 for VG bitumen and 2.5-4 for PMB bitumen) prescribed for DBM-II mixes (Figure 3). Bulk specific gravity (Gmb) values ranged between 2.34–2.40 g/cc, showing little variation between binder types.

In terms of filler influence, GGBS (GTM mixes) consistently produced the highest stability values, followed by stone dust (STM mixes), while fly ash (FTM mixes) exhibited comparatively lower stability. Fly ash mixes also showed higher VMA values and slightly higher flows, suggesting a softer structural response. Overall, the results highlight that PMB-40 binders provide enhanced stability and durability potential compared to VG-40, and among fillers, GGBS proved to be the most effective in improving mix performance.

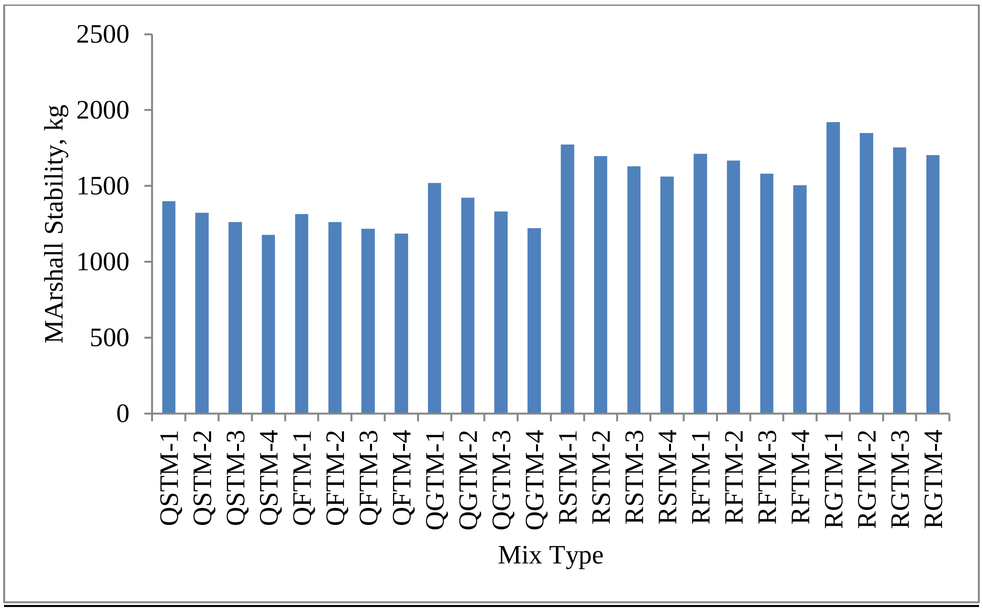

Figure 2: comparison of Marshall Stability value for all mix

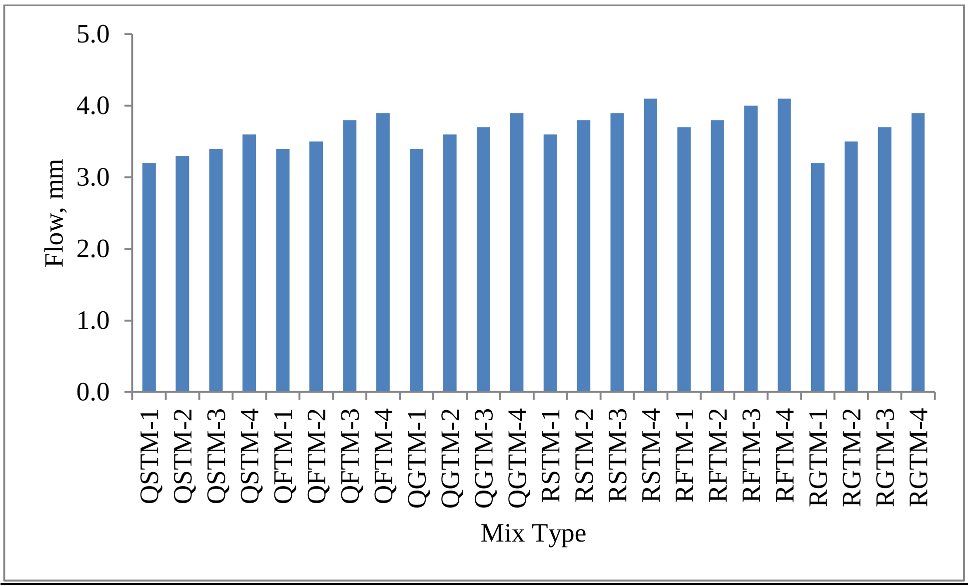

Figure 3: Comparison of Flow value for all mix

3.2 Indirect tensile strength

The indirect tensile strength (ITS) values of all mixes were observed to be well above 0.9 N/mm², indicating good tensile resistance. Among the VG-40 mixes (Q-series), ITS values ranged between **0.938 and 1.298 N/mm²,** with the highest strength recorded for QGTM-1 (1.298 N/mm²), showing the superior performance of GGBS as filler compared to stone dust and fly ash. Similarly, the PMB-40 mixes (R-series) exhibited consistently higher ITS values, ranging from **0.996 to 1.507 N/mm².** The maximum strength was obtained for RGTM-1 (1.507 N/mm²), (Figure 4) again highlighting the effectiveness of GGBS filler in combination with PMB binder. Overall, the results show that the use of PMB-40 binder improves the tensile strength compared to VG-40, and GGBS filler contributes to the highest ITS among the fillers studied.

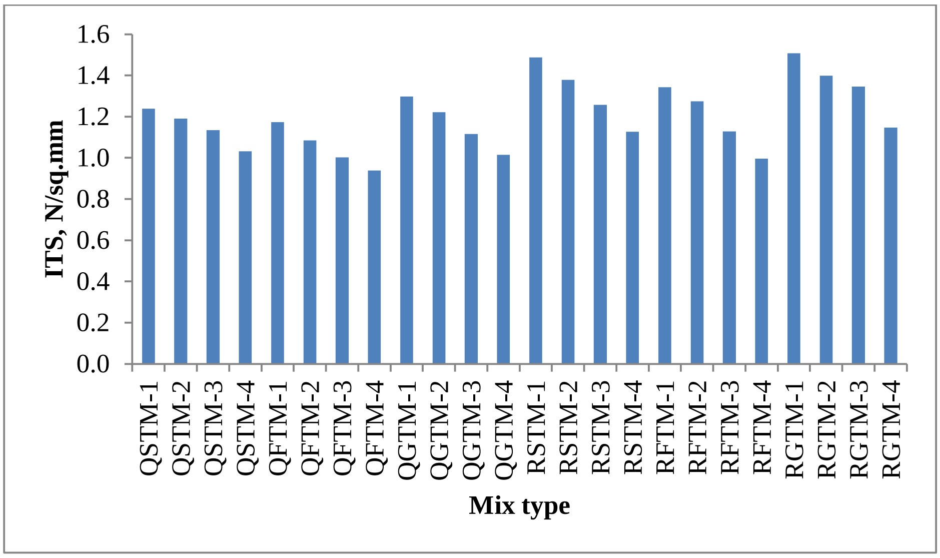

Figure 4: Comparison of ITS results of all mix

3.3 Resilient Modulus (M_R)

The resilient modulus of all mixes increased with higher RAP content, indicating enhanced stiffness due to the presence of aged binder. Among the mixes, RGTM exhibited the highest modulus values, ranging from 3987 MPa at 0% RAP to 5266 MPa at 30% RAP, followed by RSTM (3549–4622 MPa) and QGTM (3295–4978 MPa) (Figure 5). Mixes incorporating GGBS as filler generally showed superior stiffness compared to those with stone dust or fly ash, reflecting improved interfacial bonding and rigidity. According to IRC:37–2019, the recommended resilient modulus for VG-40 bituminous mixes is 3000 MPa, while for mixes prepared with modified bitumen, it is 1600 MPa. Although the experimentally obtained values exceed these limits, the recommended design values have been adopted for pavement design considerations.

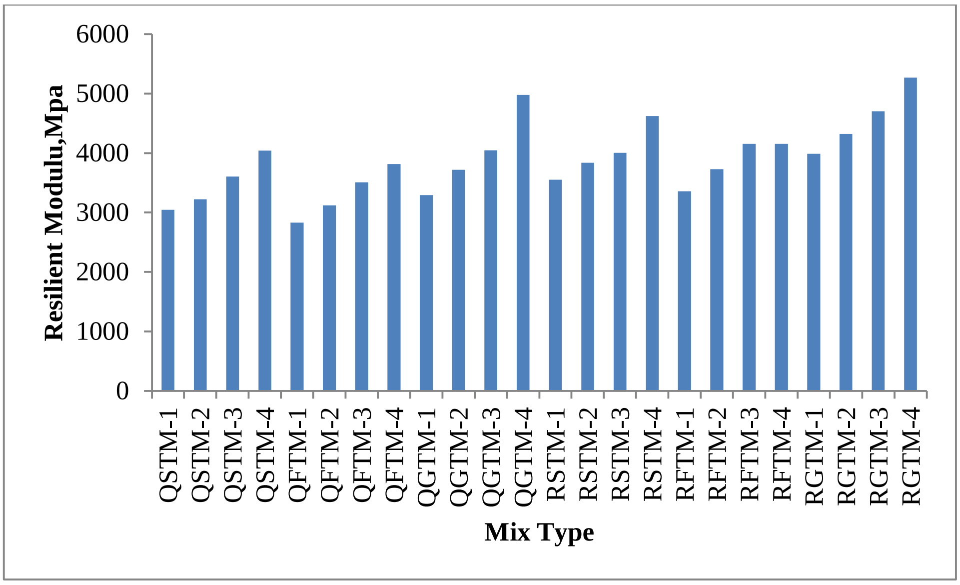

Figure 5: Comparison of M_R results of all mix

3.4 Fatigue Life (N_f)

The fatigue life of the mixes decreased with increasing RAP content (Figure 6), reflecting higher stiffness and reduced flexibility of RAP-modified binders. Among all mixes, RGTM exhibited the highest fatigue life, ranging from 17,581 cycles at 0% RAP to 11,885 cycles at 30% RAP, followed by RSTM (15,460–10,892 cycles) and QGTM (14,581–10,919 cycles). Mixes with GGBS as filler consistently showed superior fatigue resistance compared to those with stone dust or fly ash, indicating improved binder–filler interaction and better crack resistance.

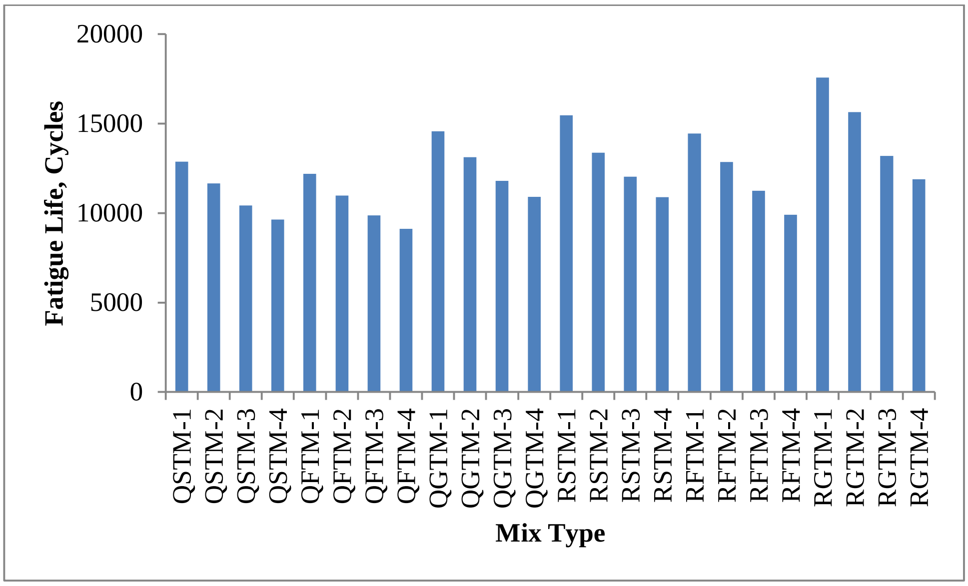

Figure 6: Fatigue life in cycles for all mixes

4. Conclusion

All the designed DBM-II mixes fulfilled the MoRTH requirements, establishing their suitability for structural pavement layers. The use of PMB-40 binder enhanced stability, tensile strength, and durability compared to VG-40, while GGBS proved to be the most effective filler, outperforming stone dust and fly ash in improving overall mix performance. Flow and volumetric properties remained within permissible limits, ensuring adequate compaction and mix consistency. The resilient modulus of the mixes increased with RAP incorporation, reflecting higher stiffness due to aged binder, though IRC-recommended values were adopted for design purposes. While fatigue life reduced with increasing RAP, GGBS-based mixes, particularly with PMB binder, demonstrated superior resistance to cracking and better durability. Overall, the results highlight that PMB-40 binder in combination with GGBS filler offers the most balanced performance for DBM-II mixes with RAP.

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