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Evaluating the Effect of Glass Grid Interface in DBM and BC with Recycled Bituminous Mix

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Abstract: Sustainable pavement engineering has become an essential requirement in modern transportation infrastructure due to rapid urbanization, increasing traffic demand, depletion of natural resources, and growing environmental concerns associated with conventional road construction. This research investigates the performance of flexible pavement mixes prepared using 30% Reclaimed Asphalt Pavement (RAP) and reinforced with glass grid at the interface of Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC) layers using VG-30 and VG-40 bitumen.

The study demonstrates that for BC mix, glass grid reinforcement significantly enhances Marshall Stability by 36% with VG-30 (24.21 kN to 32.93 kN) and 21.2% with VG-40 (21.92 kN to 26.57 kN). Composite BC-DBM systems exhibited stability improvements of 6.7% and 7.1% for VG-30 and VG-40 binders respectively compared to its counterpart. ITS values increased from 13.50 kPa to 15.03 kPa (VG-30 BC) and from 19.36 kPa to 23.69 kPa (VG-40 composite), indicating enhanced tensile crack resistance. All reinforced mixes satisfied IRC volumetric requirements with air voids maintained between 3-4% and VMA above minimum specifications.

The findings establish that 30% RAP with glass grid reinforcement is technically feasible, structurally beneficial, and promotes sustainable construction practices without compromising pavement performance.

I. INTRODUCTION

The continuous increase in traffic volume, axle loads and continuous traffic has accelerated the deterioration of flexible pavements, leading to common distresses such as rutting, fatigue cracking, reflective cracking, and permanent deformation. These challenges have increased the demand for improved pavement materials and construction techniques to enhance performance and durability. Further, the growing consumption of virgin aggregates and petroleum-based binders has raised concerns regarding the depletion of natural resources and other environmental impacts. Consequently, the highway industry has increasingly adopted recycled materials and reinforcement techniques to improve pavement performance while reducing construction costs and environmental burden. Among the available recycled materials, Reclaimed Asphalt Pavement (RAP) has emerged as an effective alternative as it reduces the demand for virgin materials and also minimize construction waste. Similarly, glass grid reinforcement has been widely used in asphalt pavements to improve tensile resistance, enhance stress distribution, delay crack propagation, and reduce permanent deformation under repeated traffic loading.

Previous studies have demonstrated that RAP can enhance pavement performance. Likewise, glass grid reinforcement has been reported to enhance rutting resistance, fatigue performance, and pavement durability through improved load transfer and crack mitigation. Although these materials have been extensively investigated individually, relatively limited attention has been given to their combined application in composite pavement systems, particularly where the reinforcement is placed at the interface between the Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC) layers. In addition, the influence of different viscosity-grade binders on the behaviour of RAP-modified, glass grid-reinforced composite mixtures has not been adequately explored.

The present study addresses this research gap by evaluating the structural performance of BC Grade-1 and DBM Grade-2 mixtures incorporating 30% RAP and reinforced with a glass grid placed at the BC–DBM interface. Two viscosity-grade binders, VG-30 and VG-40, were considered to investigate the influence of binder stiffness on the behaviour of reinforced and unreinforced mixtures. The experimental programme included Marshall Stability, volumetric analysis, Indirect Tensile Strength (ITS), and Resilient Modulus evaluation. The outcomes of this study provide experimental evidence on the effectiveness of glass grid interface reinforcement in RAP-modified flexible pavements and contribute to the development of more durable and sustainable pavement systems.

II. LITERATURE REVIEW

A. Reclaimed Asphalt Pavement (RAP) in Flexible Pavements

The use of Reclaimed Asphalt Pavement (RAP) has gained considerable attention because it reduces the consumption of virgin materials, lowers construction costs, and promotes sustainable pavement construction. Tarsi et al. (2020) reported that the United States conserved approximately 4.1 million tons of asphalt binder and 78 million tons of aggregates through RAP utilization, demonstrating its significant environmental and economic benefits. Pradhan et al. (2023) observed that RAP contents of 40-50% improved mixture stiffness and rutting resistance; however, excessive RAP increased mixture brittleness and reduced fatigue performance. Similarly, Enieb et al. (2021) identified 30% RAP as an optimum replacement level, providing a balanced combination of resilient modulus, moisture resistance, and fatigue behaviour. Salma Jaawani et al. (2021) emphasized that satisfactory performance of RAP mixtures depends on proper aggregate gradation, binder selection, and mix design, whereas Mishra (2015) reported that RAP can reduce pavement construction costs by 25-30% while meeting the requirements of IRC and MoRTH specifications. These findings indicate that RAP can provide both structural and environmental benefits when properly designed; however, its combined application with glass grid reinforcement at the BC-DBM interface has received comparatively limited attention.

B. Glass Grid Reinforcement in Flexible Pavements

Glass grid reinforcement has been widely adopted to improve the structural performance and service life of flexible pavements by enhancing tensile resistance and reducing pavement distress. Nguyen and Phan (2023) reported a 24.82% increase in flexural strength and a 7.41% reduction in rutting depth in fiberglass geogrid-reinforced pavements, demonstrating improved structural performance under repeated loading. Enieb et al. (2019) observed that glass fiber reinforcement increased fracture energy, improved tensile resistance, and reduced air voids, resulting in better compaction and durability. Similarly, Lee et al. (2019) found that glass grid-reinforced asphalt overlays exhibited lower rutting and delayed reflective cracking due to improved stress distribution at the asphalt interface. Zofka et al. (2016) reported a 15-25% reduction in asphalt tensile strain, highlighting the effectiveness of glass geogrids in mitigating crack development. Mahrez et al. (2005) also reported improvements in fatigue resistance, rutting performance, and resilient modulus, while emphasizing that reinforcement performance depends on factors such as grid location, bonding characteristics, and material compatibility. These studies demonstrate that glass grid reinforcement improves pavement performance through better stress distribution and crack control; however, its effectiveness in RAP-modified composite BC–DBM systems has not been extensively investigated.

C. Geogrid Placement and Interface Performance

The effectiveness of geogrid reinforcement is largely influenced by its placement within the pavement structure. Pandey et al. (2012) reported that placing the geogrid between the Bituminous Concrete (BC) layer and the base course reduced horizontal tensile strain by 14.96-22.35%, thereby improving resistance to fatigue cracking under both static and dynamic loading conditions. Ragni et al. (2020) observed improved shear resistance, interface adhesion, and fatigue life in reinforced asphalt interlayers, demonstrating the importance of effective load transfer across pavement layers. Graziani et al. (2014) further reported that the performance of interface reinforcement depends on grid flexibility, bonding characteristics, and compatibility with the surrounding asphalt layers. Similarly, Palla and Ram (2024) showed that geogrid reinforcement can reduce pavement thickness by 10-30% while maintaining the structural requirements specified in IRC-37:2018. Siriwardane et al. (2008) also reported a reduction in tensile strain at the bottom of asphalt layers, resulting in improved pavement resilience under repeated traffic loading. Collectively, these studies highlight that appropriate placement of geogrid reinforcement enhances load transfer, improves interlayer behaviour, and contributes to better fatigue and rutting resistance in flexible pavements

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III. RESEARCH GAPS

Although several studies have independently investigated RAP and glass grid reinforcement, limited attention has been given to their combined application in composite BC-DBM systems using different binder grades. Furthermore, the influence of glass grid placement at the BC-DBM interface in RAP-modified mixtures has not been adequately reported.

IV. OBJECTIVES OF STUDY

The present study was carried out mainly to evaluate/analyse the effect of placement of Glass grid at the interface of a typical DBM + BC layer combination which is commonly adopted using 30 % of RAP.

To achieve this the following are the objectives:

1) To prepare control mix of DBM (Grade-2) and BC (Grade-1) using RAP 30 % with VG-30 &VG-40 bitumen by Marshall method.
2) To prepare mix of BC (Grade-1) with Glass grid using RAP 30 % using VG-30&VG-40 bitumen by Marshall method.
3) To prepare composite mix (DBM + BC) with & without Glass grid using VG-30&VG-40 Bitumen and evaluate various properties by Marshall method and Indirect Tensile Strength
4) To analyses effect of placement of Glass grid on the basis of Stability & other Marshall Parameters.
5) To assess the resilient modulus of the mix with and without glass grid.

V. RESEARCH METHODOLOGY

A. *Method of Mix Design*

The Marshall mix design procedure was carried out in accordance with the MoRTH Specifications for Road and Bridge Works. BC Grade-1 and DBM Grade-2 mixes containing 30% Reclaimed Asphalt Pavement (RAP) were prepared using VG-30 and VG-40 bitumen. Five binder contents were evaluated for each mix, and three replicate specimens were prepared at each binder content to determine the optimum binder content (OBC).

Based on the selected OBC, control BC and DBM mixes, BC specimens reinforced with glass grid, and composite BC-DBM specimens with and without glass grid reinforcement were prepared. Each composite specimen consisted of 600 g of BC mix and 600 g of DBM mix placed vertically in a common Marshall mould. The specimens were evaluated using Marshall Stability, Flow, and Indirect Tensile Strength (ITS) tests, and the Resilient Modulus was estimated from the ITS results.

Fig 1: Preparation of composite BC-DBM Marshall specimen with glass grid reinforcement.

B. *Sample Details and Preparation*

Five types of specimens were prepared for the study using VG30 and VG40 bitumen:
(i) BC Grade-I control mix, (ii) DBM Grade-II control mix, (iii) BC mix with glass grid,
(iv) Composite mix with glass grid, and (v) Composite mix without glass grid.

Preparation of Reinforced Specimens

Glass grid reinforcement was positioned vertically at the centre of the specimen during preparation. Proper alignment and bonding were ensured to avoid displacement during compaction.

C. *BC with Glass Grid*

The BC specimen with glass grid was prepared by cleaning and preheating the Marshall mould. Aggregates and bitumen were heated and mixed at the optimum bitumen content (OBC). The glass grid was placed vertically at the centre of the mould, after which the BC mix was poured and compacted with 75 blows on each face. The specimen was allowed to cool, conditioned in a water bath at 60°C for 45 min, and then tested for Marshall Stability and Flow.

D. *Composite mix with Glass Grid*

The composite BC–DBM specimen with glass grid was prepared by cleaning and preheating the Marshall mould. BC and DBM mixes were prepared separately at their respective OBC and mixed at the required temperature. The glass grid was positioned vertically at the centre of the mould, followed by the vertical placement of DBM and BC mixes on either side of the grid. After removing the steel shuttering, the specimen was compacted with 75 blows on each face, cooled, conditioned in a water bath at 60°C for 45 min, and tested for Marshall Stability and Flow.

VI. MATERIAL TESTING AND RESULTS

The various tests carried out and their results are as below:

A. *Tests on Bitumen*

Two viscosity-graded bitumen binders conforming to IRC:73-2018 specifications were employed:

Table 1: Physical Properties of Bituminous used (As per IS:73-2018)

Properties	VG-30 Grade	Required	VG-40 Grade	Required	Test Method
Penetration (0.1mm)	53	50-70	42	40-60	IS:1203
Softening Point (°C)	62.5	≥ 47	66.2	≥60	IS:1205
Specific Gravity	1.01	0.99 (min.)	1.03	0.99 (min)	IS:1202

B. *Tests on Aggregates*

Aggregates for BC Grade-1 and DBM Grade-2 were tested according to IS and IRC standards.

Table 2: Physical Properties of the Aggregate used

Property	BC Grade-1 (26.5 mm)	DBM Grade-2 (37.5 mm)	Required Values
Specific Gravity	2.654	2.659	2.5-2.8 (IRC: SP:11)
Impact Value (%)	16.5	18.2	≤ 24% (IRC:111-2019 Table 1)
Elongation Index (%)	12.1	13.8	≤ 30% (IRC:111-2019)
Flakiness Index (%)	14.1	16.5	≤ 30% (IRC:111-2019)
Combined Flakiness & Elongation (%)	26.2	30.3	≤ 30% (IRC: SP:107 Table 500-10)
Water Absorption (%)	0.5	1.1	≤ 2.0% (IRC:111-2019)
L.A. Abrasion Value (%)	18.1	24.1	≤ 30% (IRC:111-2019 Table 1)

C. *Test on RAP Material*

Table 3: Physical Properties of RAP

Property	BC Grade-1 RAP	DBM Grade-2 RAP	Required Values (IRC Code)
Specific Gravity	2.62	2.64	2.4-2.7 (IRC: SP:98-2013 Cl. 5.2.1)
Impact Value (%)	15.2	16.5	≤ 27% (IRC: SP:98-2013 Cl. 5.3.2)

The bitumen content of RAP was 4.16% for BC Grade-1 RAP and 3.53% for DBM Grade-2 RAP. These values were used in the mix design.

VII. MARSHALL TEST RESULTS OF CONTROL MIX

The experimental data of various mixes with different bitumen grade and glass grid incorporation are presented in Table 4 to 6 and for comparison purpose in Fig 2 to 9. The optimum bitumen content (OBC) was selected based on maximum stability, satisfactory volumetric properties, and compliance with IRC/MoRTH requirements:

OBC for BC: Based on the Marshall mix design, the optimum binder content (OBC) for the BC mix using VG30 bitumen was found to be 5.51% and for VG40 bitumen was found to be 5.59% by weight of the total mix. At this binder content, the mix achieved a good balance of Marshall Stability, Flow, density, and air voids, satisfying the MoRTH requirements for BC mixes.

Table 4: Marshall Test Results of BC Grade-1 Control Mix for each Bitumen Content (VG30 grade)

Added Bitumen Content, % (g)	4.2(53)	4.38 (55) Optimum	4.53(57)	4.68(59)	4.83(61)
Total Bitumen Content, %	5.36	5.51	5.66	5.82	5.95
Density of compacted mix, g/cc	2.336	2.343	2.34	2.358	2.341
Specific gravity of blend aggregate	2.654	2.654	2.654	2.654	2.654
Specific gravity of mix	2.442	2.436	2.431	2.425	2.42
Volume of aggregate, Va, %	83.31	83.43	83.17	83.19	82.97
Volume of bitumen, Vb, %	12.4	12.78	13.11	13.51	13.79
Voids in mineral aggregate, VMA, %	16.69	16.57	16.83	16.81	17.03
Voids filled with bitumen, VFB, %	74.25	77.13	77.94	80.66	81.13
Air voids, Vv, %	4.29	3.79	3.71	3.3	3.34
Measured stability @ 60 °C, kN	19.39	24.21	20.73	22.46	21.07
Flow value, mm	4	4.6	5.1	5.4	5.7
Marshall Quotient	4.9	5.3	4.1	4.17	3.72

Table 5: Marshall Test Results of BC Grade-1 Control Mix for each Bitumen Content (VG40)

Added Bitumen Content, %	4.3(54g)	4.45(56g) optimum	4.61(58g)	4.76(60g)	4.91(62g)	IRC / MoRTH Requirement
Total Bitumen Content (%)	5.44	5.59	5.73	5.88	6.03	-
Density of Compacted Mix (g/cc)	2.339	2.346	2.337	2.342	2.331	-
Specific Gravity of Blend Aggregate	2.654	2.654	2.654	2.654	2.654	-
Specific Gravity of Mix	2.444	2.438	2.433	2.428	2.423	-
Volume of Aggregate, Va (%)	83.34	83.44	83.02	83.05	82.55	-
Volume of Bitumen, Vb (%)	12.35	12.73	13	13.67	13.65	-
Voids in Mineral Aggregate, VMA (%)	16.66	16.56	16.98	16.95	17.45	Min. 14%
Voids Filled with Bitumen, VFB (%)	74.15	76.89	76.59	78.87	78.25	65-75%
Air Voids, Vv (%)	4.3	3.83	3.98	3.58	3.8	3-5%
Measured Stability @ 60°C (kN)	18.72	21.92	20.16	20.92	18.24	≥ 9.0 kN
Flow Value (mm)	3.9	4.4	4.9	5.1	5.4	2-4 mm
Marshall Quotient	4.76	5.02	4.14	4.1	3.38	≥ 2.5 kN/mm

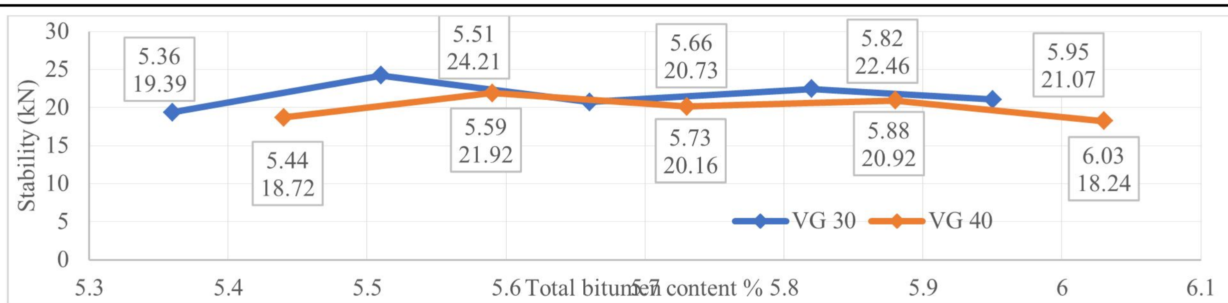

Fig 2: Stability (kN) v/s Total Bitumen Content% for BC

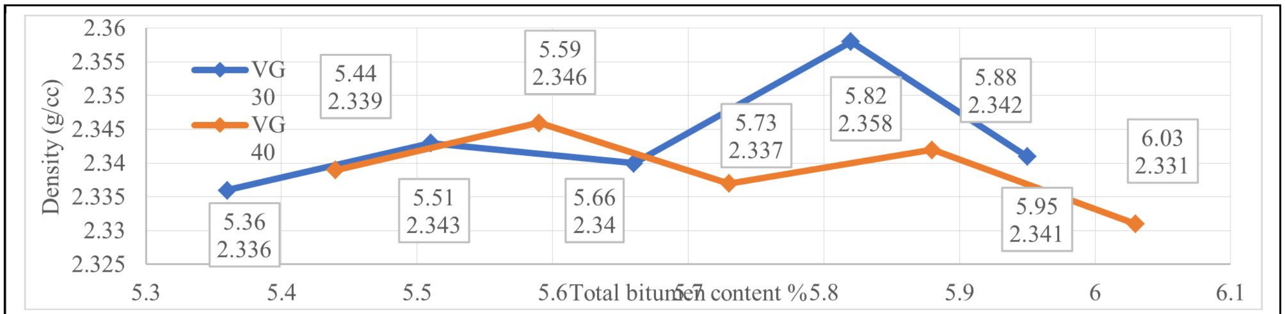

Fig 3: Density (g/cc) v/s Total Bitumen Content% for BC

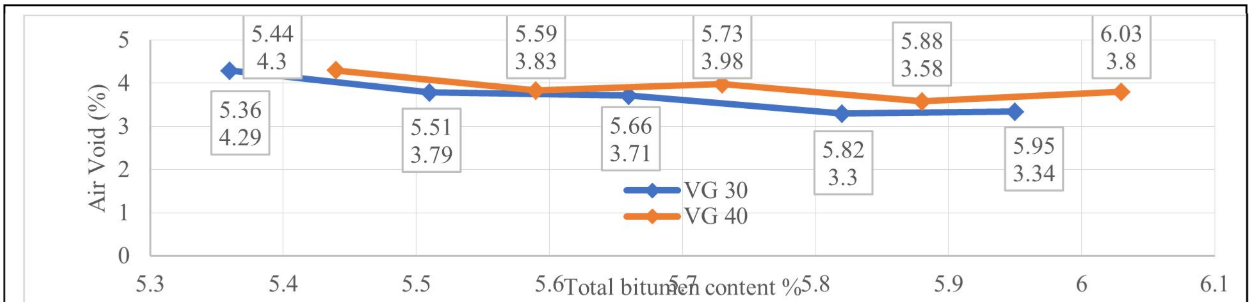

Fig 4: Air voids % v/s Total Bitumen Content % for BC

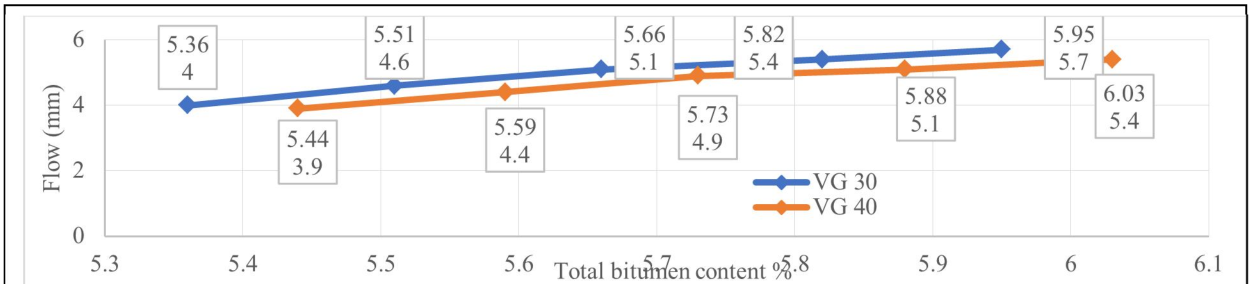

Fig 5: Flow (mm) v/s Total Bitumen Content % for BC

OBC for DBM: Based on the Marshall mix design, the optimum binder content (OBC) for the DBM mix using VG30 bitumen was found to be 5.04% and using VG40 bitumen was found to be 5.12% by weight of the total mix. At this binder content, the mix achieved the required Marshall properties and satisfied the specified volumetric criteria, indicating an optimum balance between strength and mix characteristics

Table 6: Marshall Test Results of DBM Control Mix for each Bitumen Content (VG30)

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Added Bitumen Content (%)	3.92 (49 g)	4.07 (51 g) Optimum	4.22 (53 g)	4.38 (55 g)	4.53 (57 g)	IRC / MoRTH Requirement
Total Bitumen Content (%)	4.89	5.04	5.19	5.34	5.49	-
Density of Compacted Mix (g/cc)	2.358	2.366	2.365	2.371	2.370	-
Specific Gravity of Blend Aggregate	2.659	2.659	2.659	2.659	2.659	-
Specific Gravity of Mix	2.471	2.465	2.460	2.454	2.448	-
Volume of Aggregate, Va (%)	84.35	84.49	84.31	84.40	84.23	-
Volume of Bitumen, Vb (%)	11.42	11.81	12.15	12.53	12.88	-
Voids in Mineral Aggregate, VMA (%)	15.65	15.51	15.69	15.60	15.77	Min. 12%
Voids Filled with Bitumen, VFB (%)	73.00	76.18	77.51	80.35	81.72	65-75%
Air Voids, Vv (%)	4.24	3.70	3.53	3.07	2.88	3-5%
Measured Stability @ 60°C (kN)	25.92	29.75	25.45	23.04	31.68	≥ 9.0 kN
Flow Value (mm)	3.9	4.3	4.6	4.8	5.2	2-4 mm
Marshall Quotient (kN/mm)	6.66	6.98	5.54	4.80	6.10	≥ 2.5 kN/mm

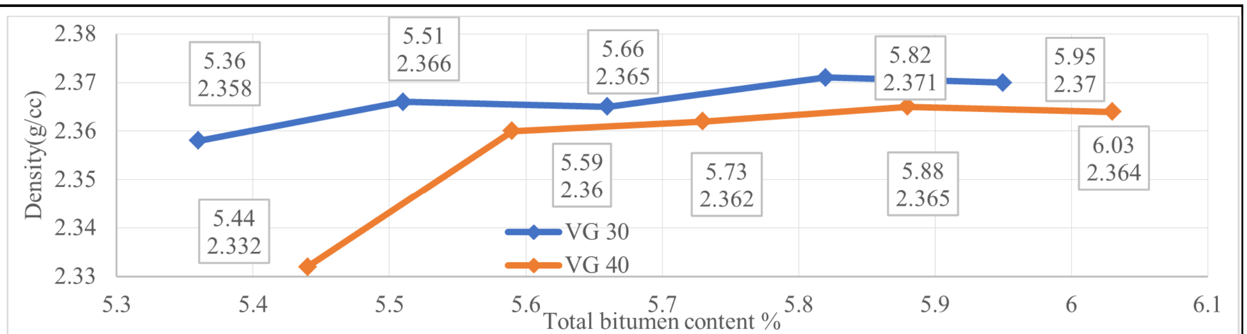

Fig 6: Density (g/cc) v/s Total Bitumen Content% for DBM

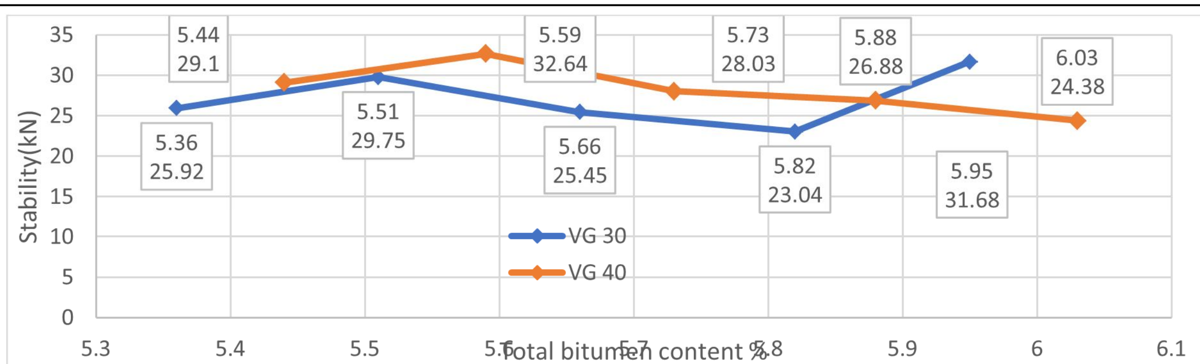

Fig 7: Stability (kN) V/S Total Bitumen Content% for DBM

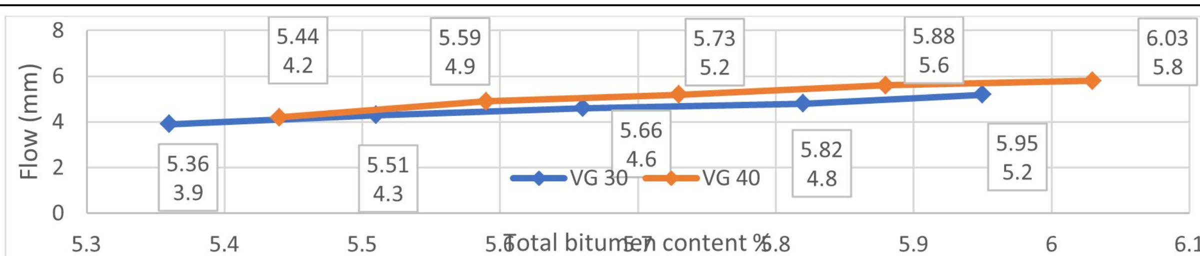

Fig 8: Flow (mm) V/S Total Bitumen Content % for DBM

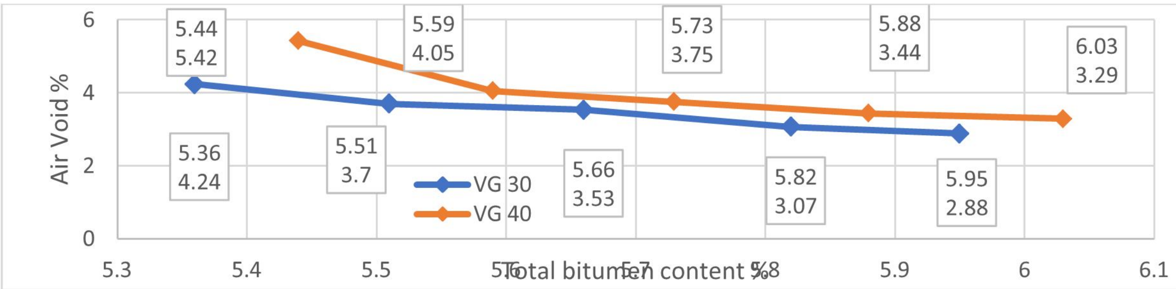

Fig 9: Air void % V/S Total Bitumen Content % for DBM

VIII. RESULTS AND DISCUSSION

A. BC Mixes with VG30 Bitumen

The Marshall properties of BC mixes prepared using VG30 bitumen with and without glass grid reinforcement are presented in Table 7.

Table 7: Comparison of BC (VG30) with Glass Grid and without Grid

	BC Without Grid VG-30	BC With Grid VG-30
Added Bitumen Content, % (Gram)	4.38 (55)	4.38 (55)
Total Bitumen Content, %	5.51	5.51
Density of compacted mix, g/cc	2.343	2.359
Specific gravity of blend aggregate	2.654	2.654
Specific gravity of mix	2.436	2.436
Volume of aggregate, Va, %	83.43	84.0
Volume of bitumen, Vb, %	12.78	12.87
Voids in mineral aggregate, VMA, %	16.57	16.0
Voids filled with bitumen, VFB, %	77.13	80.44
Air voids, Vv, %	3.79	3.13
Measured stability @ 60 °C, kN	24.21	32.93
Flow value, mm	4.6	4.6
Marshall Quotient	5.30	7.16

The inclusion of the glass grid considerably improved the Marshall performance of the VG-30 BC mix. A noticeable increase in Marshall Stability was achieved, indicating better load distribution and improved confinement of the aggregates within the mix. The Marshall Quotient also increased, while the flow value remained unchanged, showing that the reinforcement enhanced the stiffness of the mix without affecting its flexibility. In addition, the reinforced mix showed slightly higher density, lower air voids, and higher VFB, suggesting improved compaction and binder distribution. Overall, the glass grid improved the strength and deformation resistance of the BC mix while satisfying the Marshall design requirements.

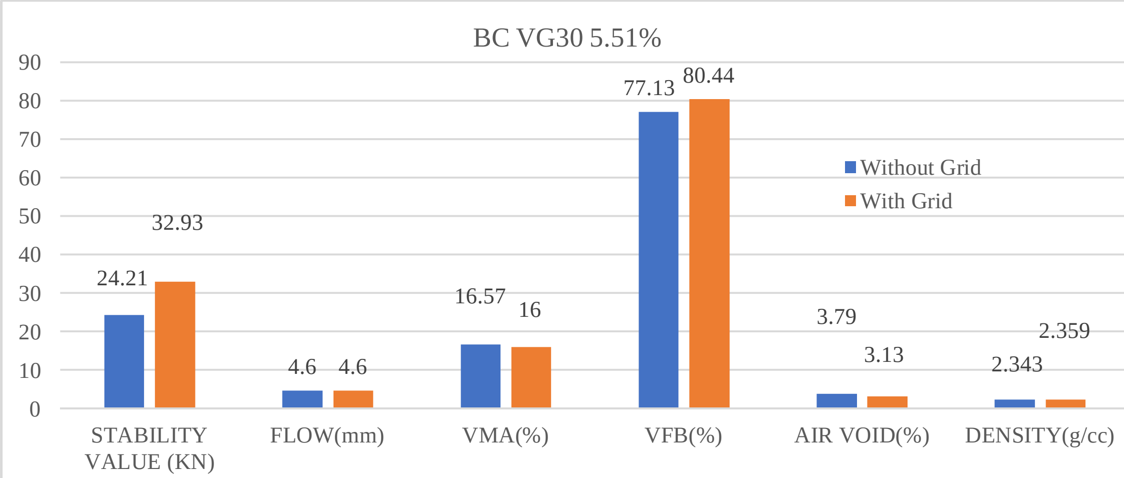

Fig 10: Graphical Representation of Marshall Properties of BC (VG-30) With and Without Glass Grid

B. BC Mixes with VG40 Bitumen

The Marshall properties of BC mixes prepared using VG-40 binder are presented in Fig 11.

The incorporation of the glass grid improved the Marshall characteristics of the VG-40 BC mix. An increase in Marshall Stability showed that the reinforcement helped the mix resist higher loads by improving aggregate confinement and load distribution. The higher Marshall Quotient, together with only a slight increase in the flow value, indicates that the mix gained stiffness while maintaining adequate flexibility. In addition, the reinforced mix showed improved volumetric properties, including higher density, lower air voids, and increased VFB, which indicate better compaction and binder distribution. Overall, the glass grid enhanced the strength and deformation resistance of the VG40 BC mix while meeting the Marshall mix design requirements.

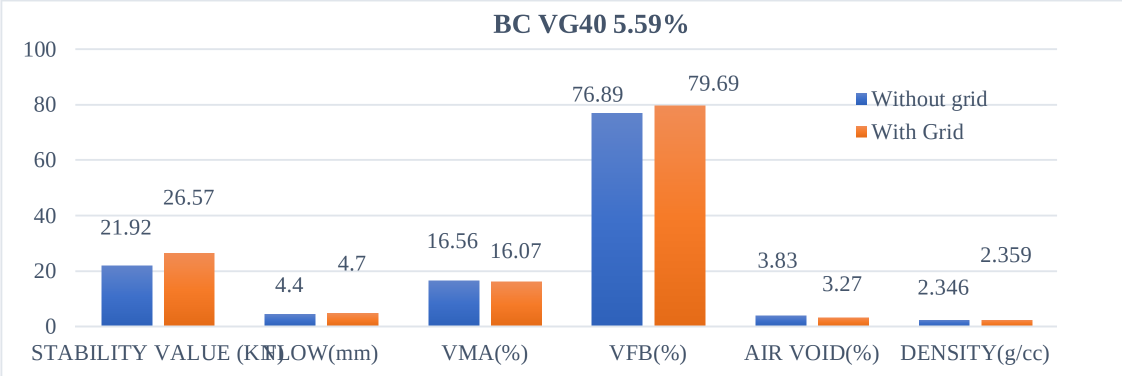

Fig 11: Graphical Representation of Marshall Properties of BC (VG-40) With and Without Glass Grid

C. Composite Mixes with VG-30 Bitumen

The Marshall properties of composite VG-30 mixes are presented in Table 8.

Table 8: Comparison of Composite Mix (VG30) with Glass Grid and without Grid

COMPOSITE MIX VG-30		
	BC	DBM
Sample Mixture (Gram)	600	600
Weight of Aggregate, g	222	240
Weight of Stone Dust, g	186	180
Weight of RAP, g	180	180
Weight of Cement, g	12	--
Added Bitumen Content, % (Gram)	4.38 (27.5)	4.07(25.5)

Bitumen Content in RAP, % (Gram)	4.16 (7.48)	3.53(6.35)
Total Bitumen Content, %	5.27	
	Composite mix without Grid VG30	Composite mix with Grid VG30
Density of compacted mix, g/cc	2.35	2.354
Specific gravity of blend aggregate	2.657	2.657
Specific gravity of mix	2.44	2.44
Volume of aggregate, Va, %	83.78	83.94
Volume of bitumen, Vb, %	12.26	12.28
Voids in mineral aggregate, VMA, %	16.22	16.06
Voids filled with bitumen, VFB, %	75.62	76.47
Air voids, Vv, %	3.96	3.78
Measured stability @ 60 °C, kN	30.32	32.36
Flow value, mm	4.2	5.30
Marshall Quotient	7.22	6.11

The addition of the glass grid improved the overall performance of the composite VG-30 mix. The increase in Marshall Stability indicates that the reinforcement enhanced the bond between the BC and DBM layers, allowing the specimen to carry higher loads. A higher flow value was also observed, showing that the composite mix could undergo greater deformation before failure. As a result, the Marshall Quotient decreased slightly because of the increased flow, although the stability of the mix improved. The reinforced specimen also showed better volumetric properties, including slightly higher density, lower air voids, and higher VFB, indicating improved compaction and binder distribution. These results suggest that the glass grid effectively strengthened the BC-DBM interface and improved the overall behaviour of the composite pavement system.

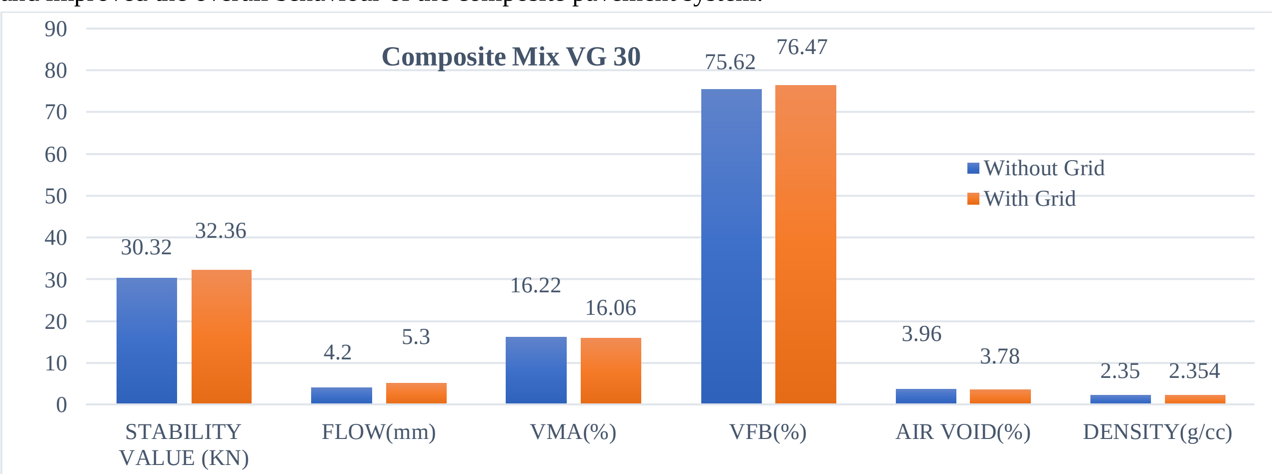

Fig 12: Graphical Representation of Marshall Properties of Composite Mix (VG-30) With and Without Glass Grid

D. Composite Mixes with VG-40 Bitumen

The Marshall properties of composite VG40 mixes are shown in Fig 13.

The addition of the glass grid enhanced the performance of the composite VG-40 mix by improving the interaction between the BC and DBM layers. A noticeable increase in Marshall Stability confirmed better load transfer across the interface, while the higher flow value indicated that the reinforced specimen could sustain greater deformation before failure. Although the Marshall Quotient decreased slightly due to the increase in flow, the reinforced mix maintained higher strength than the unreinforced specimen. The reinforced composite also exhibited improved volumetric properties, including slightly higher density, lower air voids, and higher VFB, indicating better compaction and binder distribution. Overall, the combination of VG-40 bitumen and glass grid reinforcement produced the best overall Marshall performance among all the mixes evaluated.

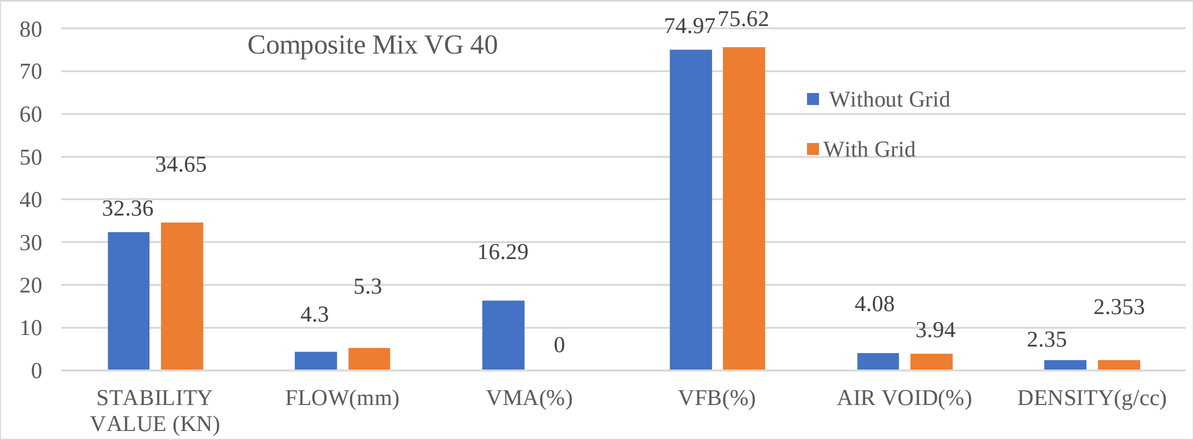

Fig 13: Graphical Representation of Marshall Properties of Composite Mix (VG-40) with and without Glass Grid

E. *Comparative Analysis of VG-30 and VG-40 Mixes*

The comparative analysis indicates that both VG-30 and VG-40 mixes benefited from glass grid reinforcement. The VG-30 mixes showed a greater percentage improvement in Marshall properties, suggesting that the reinforcement was more effective in improving the performance of the relatively softer binder. In comparison, the VG-40 mixes exhibited higher absolute Marshall Stability and Marshall Quotient values due to the higher stiffness of the binder. The combination of VG-40 bitumen and glass grid provided superior structural strength and better resistance to permanent deformation, making it suitable for heavy traffic conditions. On the other hand, the reinforced VG-30 mixes offered better flexibility and deformation tolerance, making them more appropriate for pavements where fatigue and cracking are major concerns. Overall, the performance of the glass grid was influenced by the stiffness of the binder, with VG-30 favouring flexibility and VG-40 providing higher structural stability.

F. *Indirect Tensile Strength (ITS) Analysis*

Marshall Stability alone cannot fully represent the tensile cracking behaviour of pavement systems under repeated traffic loading. Therefore, Indirect Tensile Strength (ITS) testing was conducted to evaluate the tensile resistance and crack propagation characteristics of reinforced and unreinforced mixes.

Table 9: Indirect Tensile Strength Results

Mix Type	Without Grid (kPa)	With Grid (kPa)	Improvement
BC VG-30	13.50	15.03	+11.3%
BC VG-40	17.58	19.36	+10.1%
Composite VG-30	15.54	18.34	+18.0%
Composite VG-40	19.36	23.69	+22.4%

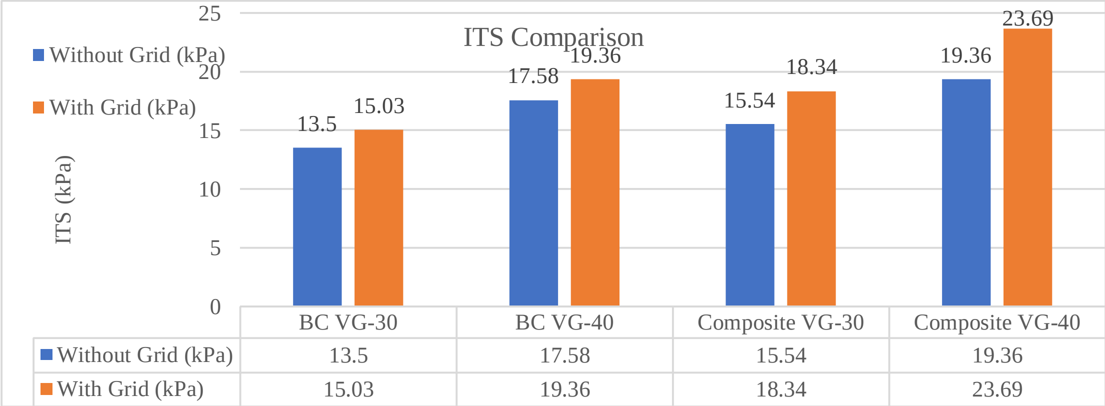

Fig 14: ITS Comparison Table

The ITS results clearly indicate that glass grid reinforcement improved tensile strength for all specimens.
The highest improvement was observed in reinforced composite VG-40 specimens, where ITS increased by approximately 22.4%.
This confirms that glass grid reinforcement is highly effective at the DBM-BC interface where tensile stresses are concentrated.
Higher ITS values indicate improved resistance against fatigue cracking and reflective cracking, which are among the most common distress mechanisms in flexible pavements.
The reinforcement layer redistributed tensile stresses more effectively and delayed crack initiation and propagation.

G. Resilient Modulus (Mr) Analysis

Resilient Modulus represents the elastic response and recoverable deformation characteristics of pavement materials under repeated loading.
The Resilient Modulus was calculated using:

$$M_r = 1.1991 \times ITS + 1170$$

Table 10: Resilient Modulus Results

Mix Type	Without Grid (MPa)	With Grid (MPa)	Increase
BC VG-30	1186.19	1188.02	+0.15%
BC VG-40	1191.08	1193.21	+0.18%
Composite VG-30	1188.63	1191.99	+0.28%
Composite VG-40	1193.21	1198.41	+0.44%

The improvement in resilient modulus, together with the increase in Marshall Stability and ITS, indicates that the glass grid enhanced both the strength and elastic response of the pavement system. This combination is desirable for flexible pavements, as it improves load-carrying capacity while maintaining adequate flexibility under repeated traffic loading.

H. Volumetric Properties and IRC Compliance

All specimens satisfied IRC and MoRTH volumetric requirements.
The obtained air voids, VMA, VFB, and stability values were within permissible limits, confirming the suitability of the mixes for pavement construction.
The slight increase in VFB observed in reinforced mixes is attributed to improved compaction and densification caused by the restraining effect of the glass grid.
No bleeding or instability was observed in any reinforced specimen.

I. Practical Implications of the Study

The results of the present investigation have important practical implications for pavement engineering.

1) The significant increase in Marshall Stability indicates the possibility of reducing pavement thickness while maintaining structural performance. The 36% stability increase for BC VG-30 allows potential pavement thickness reduction of 10–15% while maintaining structural capacity.
2) Higher ITS (up to +22%) indicates better fatigue and crack resistance, leading to longer pavement life and lower maintenance costs.
3) The use of 30% RAP significantly reduces the demand for virgin aggregates and bitumen, thereby lowering construction costs and environmental impact.
4) Reinforced VG-40 composite systems are highly suitable for heavy traffic corridors and high-temperature regions.

5) Glass grid reinforcement can increase pavement service life and reduce maintenance frequency, resulting in lower lifecycle costs.
6) The combined use of RAP and glass grid reinforcement provides a sustainable, economical, and high-performance solution for modern flexible pavement construction.
7) Laboratory vs. field conditions: In this study, the glass grid was placed vertically inside Marshall specimens due to mould constraints. In actual field construction, the grid is laid horizontally and compacted with rollers, which provides better alignment and confinement. Therefore, the reported improvements are conservative; field performance is expected to be better.

J. *Summary of Results*

Table 11: Comparative Performance of Reinforced and Unreinforced RAP-Modified BC and Composite DBM-BC Mixes

	BC VG-30		BC VG-40		Composite VG-30		Composite VG-40	
	Without Glass grid	With Glass grid	Without Glass grid	With Glass grid	Without Glass grid	With Glass grid	Without Glass grid	With Glass grid
Marshall Stability (kN)	24.21	32.93	21.92	26.57	30.32	32.36	32.36	34.65
Flow Value (mm)	4.57	4.6	4.37	4.74	4.2	5.3	4.3	5.3
Marshall Quotient	5.3	7.16	5.02	5.61	7.22	6.11	7.53	6.54
ITS (kPa)	13.5	15.03	17.58	19.36	15.54	18.34	19.36	23.69
Resilient Modulus (MPa)	1186.19	1188.02	1191.08	1193.21	1188.63	1191.99	1193.21	1198.41

In Table 11 it presents a comparative summary of the performance of reinforced and unreinforced RAP-modified BC and composite DBM-BC mixes. The results show that glass grid reinforcement improved the structural and mechanical properties of both BC and composite mixes. The BC mix prepared with VG-30 bitumen exhibited the highest percentage improvement in Marshall Stability, while the reinforced composite mix prepared with VG-40 bitumen achieved the highest Marshall Stability, Indirect Tensile Strength, and Resilient Modulus values among all the mixes investigated. Overall, the results indicate that the incorporation of glass grid reinforcement enhances the performance of RAP-modified bituminous mixes and improves the behaviour of the composite pavement system.

IX. CONCLUSIONS

1) The optimum binder content (OBC) was established as 4.38% for BC (VG30), 4.45% for BC (VG40), 4.07% for DBM (VG30), and 4.15% for DBM (VG40) based on the Marshall mix design procedure. The reduction in binder content values are attributed to use of RAP.
2) Using 30% RAP in BC and DBM mixes is acceptable without compromising the requirements of IRC and MoRTH specifications.
3) Glass grid reinforcement enhanced the Marshall performance of both BC and composite mixes. The BC mix with VG30 exhibited the highest improvement in Marshall Stability, whereas the composite mix with VG40 achieved the highest overall stability among the reinforced specimens.
4) Reinforced composite specimens exhibited improved Stability values which may be due to improved interlayer bonding and stress transfer at the BC-DBM interface, resulting in higher load-carrying capacity. The reinforced mixes showed improved volumetric characteristics, including slightly higher density, lower air voids, and higher VFB, indicating better compaction and binder distribution while maintaining the required mix design criteria.
5) Glass grid reinforcement increased the Indirect Tensile Strength (ITS) of all mixes, indicating improved resistance to tensile stresses, fatigue cracking, and reflective cracking. The highest ITS was obtained for the reinforced composite VG40 mix.
6) A marginal increase in Resilient Modulus was observed for all reinforced specimens, indicating improved elastic response under repeated loading. The highest resilient modulus was also recorded for the reinforced composite VG40 mix.

7) The comparative evaluation showed that VG30 mixes exhibited greater relative improvement after reinforcement, whereas VG40 mixes provided higher overall structural capacity because of the higher stiffness of the binder.
8) The combined use of 30% RAP and glass grid reinforcement offers a technically feasible and sustainable approach for flexible pavement construction. Among all the mixtures evaluated, the reinforced composite VG40 mix demonstrated the best overall performance and is recommended for pavements subjected to heavy traffic and high service temperatures.
9) The combined use of RAP and glass grid reinforcement can reduce the consumption of virgin aggregates and bitumen, lower construction waste and improve the overall sustainability of flexible pavement construction

X. PRACTICAL RECOMMENDATIONS

1) Glass grid reinforcement should preferably be placed at the DBM-BC interface during new flexible pavement construction, as this results in integral response to stress transfer.
2) For pavement rehabilitation and overlay works, glass grid may be placed within or immediately below the BC layer to delay crack propagation from existing pavement layers and improve fatigue performance.
3) The composite DBM-BC mix prepared with VG40 bitumen and reinforced with glass grid may be adopted for national highways, expressways, industrial corridors, and other heavy traffic pavements because of its higher stability, stiffness, and load-carrying capacity.
4) The composite DBM-BC mix prepared with VG30 bitumen and reinforced with glass grid is recommended for urban roads and medium traffic pavements because of its better flexibility and strain absorption.
5) The use of 30% RAP may be safely adopted in BC and DBM mixes, provided that proper RAP characterization, binder content evaluation and quality control procedures are followed.
6) During construction, proper placement of the glass grid need to be done to achieve desired results.
7) The combined use of RAP and glass grid reinforcement can reduce the consumption of virgin aggregates and bitumen, lower construction waste and improve the overall sustainability of flexible pavement construction.

XI. LIMITATIONS OF THE PRESENT STUDY

1) The laboratory specimens were prepared with the glass grid placed vertically because of the dimensional limitations of the Marshall mould. In actual pavement construction, the glass grid is installed horizontally at the interface of asphalt layers. Therefore, the laboratory specimen configuration partially represent field practice.
2) Because the direction of Marshall hammer compaction differed from field roller compaction, slight movement of the vertically positioned glass grid during compaction could not be completely avoided. This may have caused minor variations in the measured response of the reinforced specimens.
3) The investigation was limited to Marshall Stability, volumetric properties, Indirect Tensile Strength (ITS), and Resilient Modulus. Other performance characteristics, including fatigue behaviour, rutting resistance, moisture susceptibility, and thermal cracking, were not evaluated.
4) The study was conducted entirely under controlled laboratory conditions. Consequently, the long-term performance of the reinforced pavement system under actual traffic loading and environmental conditions could not be assessed.

XII. FUTURE SCOPE

1) Field-scale investigations should be carried out to evaluate the long-term performance of 30% RAP and glass grid reinforced pavements under actual traffic and environmental conditions.
2) The performance of reinforced mixtures should be evaluated using fatigue, rutting, moisture susceptibility, and thermal cracking tests to assess their long-term durability.
3) Advanced laboratory tests such as the Wheel Tracking Test, Dynamic Modulus Test, Four-Point Bending Fatigue Test, and Semi-Circular Bend (SCB) Test may be conducted to obtain a more comprehensive understanding of the mechanical behaviour of reinforced asphalt mixtures.
4) The influence of different RAP contents (40%, 50%, and higher) and glass grids with different tensile strengths should be investigated to identify the optimum reinforcement configuration for flexible pavements.
5) Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) should be performed to evaluate the long-term economic and environmental benefits of RAP and glass grid reinforcement.

6) The effect of placing the glass grid at different pavement interfaces (within BC, at the BC–DBM interface, and between DBM and the granular base) should be investigated to determine the most effective reinforcement location.
7) Long-term field monitoring is recommended to correlate laboratory observations with in-service pavement performance and to support the development of practical design guidelines for glass grid reinforced flexible pavements

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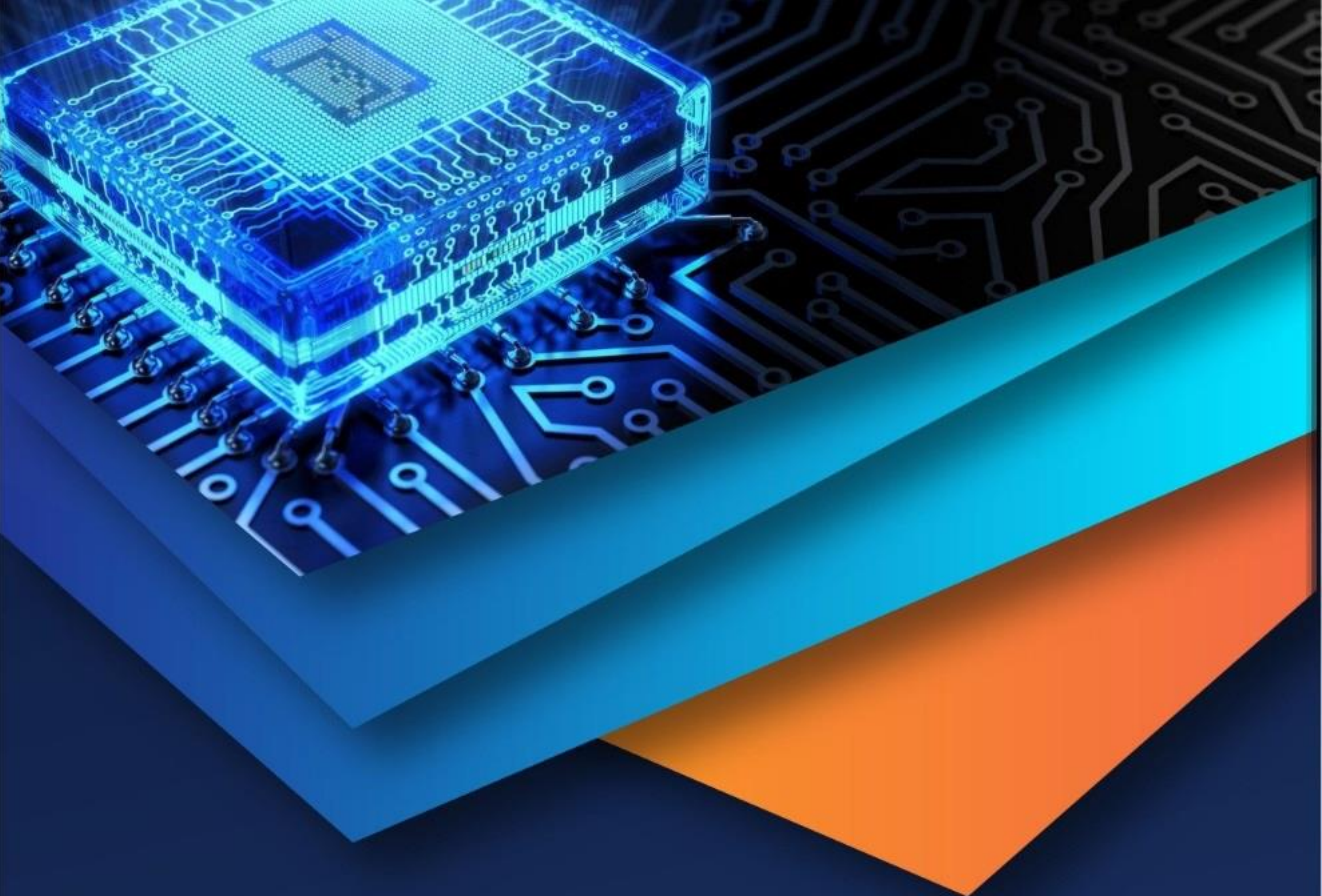

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