Study & Experimentation on Application of Recycled Asphalt Shingles (RAS) as a Hot Mix Asphalt

Dhananjay Kumar Singh[1], S.S. Kushwaha[2]

[1]Ph.D. Scholar Dept. of Civil Engineering Rabindranath Tagore University Bhopal (M.P. India)

[2]Assistant Professor, School of Civil Engineering, Shri Mata Vaishno Devi University, Katra(J&K India)

HOW TO CITE:

Dhananjay Kumar Singh, S.S. Kushwaha (2026). Study & Experimentation on Application of Recycled Asphalt Shingles (RAS) as a Hot Mix Asphalt. International Journal of Special Education, 41(7s), 303-316.

COPYRIGHT STATEMENT:

Copyright: © 2026 Authors. Open access publication underthe terms and conditions of the Creative CommonsAttribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

ABSTRACT:

This study investigates the performance of Hot Mix Asphalt prepared using Recycled Asphalt Shingles (RAS) and Reclaimed Asphalt Pavement (RAP) for the Bahadurganj–Araria section of NH-327E. The study includes selection and characterization of materials, sieve analysis, gradation design, Marshall specimen preparation, and performance evaluation of the modified asphalt mix. VG-30 bitumen, lime filler, and rejuvenator were used along with recycled constituents to develop a sustainable and workable mix. Marshall mix design results showed that the optimum bitumen content was 5.8%, at which the mix achieved maximum stability, proper density, and acceptable air voids. The developed mix satisfied the required MORTH specifications and demonstrated satisfactory engineering performance. The study concludes that RAP and RAS can be effectively used in hot mix asphalt to improve sustainability while maintaining adequate pavement performance

Keywords: Recycled Asphalt Shingles (RAS), Reclaimed Asphalt Pavement(RAP), Hot Mix Asphalt(HMA), Marshall Mix Design, Optimum Bitumen Content, Sustainable Pavement

1. Introduction

India's road construction still relies heavily on virgin aggregates and bitumen, which increases cost and places pressure on natural resources, while recycled materials such as RAP and RAS can reduce waste and support sustainable pavement construction (FHWA, 2025; TRB, 2014). The main problem in this study is to determine whether Recycled Asphalt Shingles can be effectively used in Hot Mix Asphalt for the Bahadurganj–Araria section of NH-327E without reducing pavement quality under local traffic and climatic conditions (TRB, 2014; Shingle Recycling, 2025). Therefore, the objectives of this research are to evaluate the performance of RAS and RAP in Hot Mix Asphalt, determine the optimum bitumen content through Marshall mix design, and verify whether the recycled mix meets the required engineering and performance criteria while supporting cost-effective and sustainable road construction (FHWA, 2025; TRB, 2014)

Recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) have been widely studied as sustainable alternatives in asphalt mixtures because they reduce the use of virgin materials while maintaining acceptable engineering performance. Aurangzeb et al. (2012) showed that mixtures with high RAP content can achieve desired volumetrics and performance when mix design is properly controlled. Bennert et al. (2014) also reported that higher RAP percentages can be successfully incorporated through appropriate implementation strategies, demonstrating the practical feasibility of recycled mixtures in pavement construction. Ghabchi et al. (2016) found that asphalt mixes containing RAP and RAS can be characterized effectively in the laboratory, confirming that these

recycled materials can contribute to mixture stiffness and overall performance. Hand and Aschenbrener (2023) further noted that field case studies of RAS use have provided important lessons for improving mixture design and construction practices. Mivehchi et al. (2022) emphasized that asphalt mixes with high percentages of RAP and RAS require careful design measures to balance performance, durability, and workability. In addition, Hansen and Newcomb (2010) documented the growing use of RAP, RAS, and warm-mix asphalt in production practice, reflecting the increasing acceptance of recycled materials in the pavement industry. Briere (2000) described the importance of mix design fundamentals in achieving stable and durable hot-mix asphalt, which remains relevant when designing recycled mixtures. Behnood and Modiri Gharehveran (2019) highlighted that binder morphology and rheological behavior strongly influence asphalt performance, reinforcing the need to control aged binder characteristics in recycled asphalt systems. Overall, these studies confirm that RAP and RAS can improve sustainability and reduce material consumption, but successful application depends on mix design, binder balance, and local performance requirements.

2. Methodology

2.1 Materials and Their Properties Used in the Study

The recycled materials used in this study were Recycled Asphalt Shingles (RAS) and Reclaimed Asphalt Pavement (RAP), collected from Araria for use as recycled constituents in the asphalt mix. RAS contains aged asphalt binder, mineral fillers, and fibers, and was crushed, screened, and cleaned before mixing. Virgin aggregates of 13.2 mm and 6 mm sizes were sourced from Pakur, Jharkhand, and were selected for their angular shape, good gradation, abrasion resistance, and strength. VG-30 bitumen, obtained from IOCL Barauni, Bihar, was used as the binder and tested for penetration, viscosity, and softening point to confirm its suitability for Hot Mix Asphalt. Lime was used as mineral filler, collected from Neelkanth Industries, Rajasthan, to improve density and stability of the mix. A rejuvenator procured from Zydex Industries, Patparganj, Delhi, was added to restore the properties of the aged binder in RAS and RAP and improve flexibility, workability, and cracking resistance.

Table 1: Selected Materials, Initial Proportions and Basic Properties Used in the Asphalt Mix

Sr. No.	Materials	Selected Percentage (%)	Property	Value	Remarks
1	RAP + RAS (TOSS)	32.50	Binder Content (RAS)	18–30%	Aged binder present
			Binder Content (RAP)	4–6%	Additional aged binder
			Specific Gravity	1.1–2.6	Depends on source
			Nature	Aged and stiff	Recycled material
2	Virgin Aggregate (13.2 mm)	20.50	Specific Gravity	2.6–2.8	As per standards
			Water Absorption	< 2%	Good quality
			Impact Value	< 30%	Strength indicator

3	Virgin Aggregate (6 mm)	45.00	Specific Gravity	2.6–2.8	Well graded
			Gradation	As per MORTH	Suitable for DBM mix
4	Lime	2.00	Specific Gravity	2.2–2.4	Mineral filler
			Passing 0.075 mm sieve	≈ 99%	Acts as filler
5	VG-30 Bitumen	2.48	Penetration	50–70 mm	As per IS 73
			Softening Point	47–55°C	Temperature resistance

2.2 Sieve Analysis and Aggregate Gradation

After the selection of materials, sieve analysis and aggregate gradation were carried out to determine the particle size distribution of the combined aggregate blend. The blend included RAP + RAS, virgin aggregate of 13.2 mm, virgin aggregate of 6 mm, and lime filler. The results were compared with MORTH gradation limits to ensure that the mix satisfied the required grading pattern. Mid values were also calculated to check the deviation of the achieved gradation from the standard grading band. The gradation results showed that the combined blend was properly proportioned and suitable for Hot Mix Asphalt preparation

The gradation analysis confirms that the RAP + RAS modified bituminous mix meets MoRTH BC G-II specifications across all sieve sizes. All % passing values fall within limits, with maximum variations of +1.90% at 9.50 mm and +1.73% at 0.600 mm. The 0.075 mm sieve shows 6.71% passing (within 4–10%), indicating adequate filler content for proper binder-aggregate interaction and mixture stability. The continuous gradation demonstrates proper blend design and effective RAP + RAS integration with virgin aggregates. This compliant aggregate skeleton supports the observed satisfactory rutting resistance (4.0 mm), fatigue performance (700 cycles), and moisture resistance (TSR ≥ 0.80), confirming that 31.53% recycled content is technically viable for bituminous concrete while maintaining structural integrity

2.3 Basic Properties of Binder and Final Mix Design

As per (IS:73:2013)The penetration value of 65 mm confirms proper consistency for HMA applications as per VG-30 grade specifications. The softening point of 52°C confirms adequate temperature resistance for high-temperature pavement performance. The absolute viscosity of 2650 P at 60°C indicates suitable workability for mixing and compaction.After fixing the binder and aggregate proportions, the total binder and rejuvenator content was adjusted to 2.98%, leaving 97.02% for RAP + RAS, virgin aggregates, and filler. The optimized mix finally contained 31.53% RAP + RAS, 19.89% virgin aggregate (13.2 mm), 43.66% virgin aggregate (6 mm), 1.94% lime, 2.48% VG-30 bitumen, and 0.50% rejuvenator. Marshall specimens were prepared at 5.4%, 5.6%, 5.8%, 6.0%, and 6.2% bitumen contents, and the optimum bitumen content was selected based on maximum Marshall Stability, maximum bulk specific gravity, and approximately 4% air voids.

3. Test and Analysis

3.1 VG-30 Bitumen Test

VG-30 bitumen was tested separately to confirm its basic engineering properties before mix preparation. The main tests were penetration test, softening point test, and absolute viscosity test shown in Figure 1.The penetration value of 65 mm showed that the binder had moderate consistency and was suitable for pavement use. The softening point of 52°C indicated good resistance to temperature rise, which is important for hot climate conditions. The absolute viscosity range

of 2650P at 60°C showed satisfactory flow and workability during mixing and compaction. Overall, these results confirmed that VG-30 bitumen was suitable for use in the recycled Hot Mix Asphalt.

(a) Viscosity of VG-30 Bitumen

(b) Penetration Test

(c) Softening Point Test

Figure 1: Laboratory Testing for Determination of VG-30 bitumen

Table 2: Result of VG-30 Bitumen

Sr. No.	Property	Value	Remarks
1	Penetration	65 mm	As per VG-30 grade
2	Softening Point	52°C	Suitable temperature resistance
3	Absolute Viscosity at 60°C	2650P	Suitable workability

3.2 Final Mixing

3.2.1 Final Sample Prepared : After evaluating VG-30 bitumen, the final asphalt mix was prepared using RAP + RAS, virgin aggregates, lime filler, VG-30 bitumen, and rejuvenator. The final sample was successfully produced in the laboratory, showing that the selected mix proportions were suitable for further testing and evaluation as per (ASTM D 2172 and ASTM D 5444).

Figure 2 : Final Sample Prepared from RAP + RAS + Virgin Materials (Final Mix) in Laboratory

3.2.2 Binder Content Determination of Final Mix: The binder content determination test was carried out to check the total binder present in the final mix prepared with RAP, RAS, and virgin materials. The sample was tested by extraction under controlled laboratory conditions, and the test confirmed the binder contribution from both reclaimed and virgin sources as per (ASTM D 2172 and ASTM D 5444).

Figure 3: Laboratory Testing for Determination of Binder Content of RAP + RAS + Virgin Materials (Final Mix)

Table 3: Binder Contribution in the Final Mix

Source	Binder Content (%)
RAP	1.45
RAS	1.88
Virgin Binder	2.48
Total	**5.80**

Table 3 shows that the total binder content of the final asphalt mix comprised 1.45 percent from RAP, 1.88 percent from RAS, and 2.48 percent from virgin binder, giving a total binder content of 5.80 percent. This indicates that the developed mix relied on a blended binder system containing both reclaimed binder and virgin binder.

3.2.3 Binder Content and Gradation Analysis of Final Mix: The binder content and gradation analysis showed that the final mix had a proper aggregate structure and remained within the required MORTH limits at all sieve sizes. This confirmed that the RAP + RAS + virgin material mix was suitable for further Marshall performance evaluation as per (ASTM D 2172 and ASTM D 5444).

Figure 4: Laboratory Testing for Determination of Binder Content and Gradation of RAP + RAS + Virgin Materials (Final Mix)

The gradation analysis showed that the final mix stayed within MORTH limits at all sieve sizes. The highest positive variation was +1.90 at the 9.50 mm sieve, while the highest negative variation was -0.66 at the 0.300 mm sieve. The 19.0 mm sieve was exactly at the specified limit, and the overall gradation followed the middle grading line, confirming that the RAP + RAS, virgin aggregates, and lime filler blend was properly proportioned and satisfactory for hot mix asphalt preparation.

3.3 Marshall Mix Design Analysis

As per (ASTM D 6927) Marshall mix design was carried out to assess the performance of the asphalt mix prepared with RAP, RAS, virgin aggregates, lime filler, VG-30 bitumen, and rejuvenator. The specimens were tested at 5.4%, 5.6%, 5.8%, 6.0%, and 6.2% bitumen content, and the Marshall and volumetric properties varied with binder content. This analysis helped identify the most suitable binder content for the recycled asphalt mix.

Table 4: Marshall Mix Design & volumetric properties Results at Different Bitumen Contents

Bitumen Content (%)	Maximum Density	Bulk Specific Gravity of Mix	Air Voids (%)	VMA (%)	VFB (%)	Stability (kg)	Flow (mm)	Marshall Quotient
5.4	2.388	2.561	6.75	15.77	57.22	902.12	2.33	3.87
5.6	2.421	2.553	5.17	14.79	65.08	1071.74	2.63	4.07
5.8	2.443	2.545	3.99	14.19	71.89	1232.70	3.27	3.77
6.0	2.439	2.537	3.85	14.52	73.49	1008.38	4.33	2.32
6.2	2.424	2.529	4.14	15.23	72.80	905.33	5.30	1.71

3.4 Analysis of Marshall Parameters:

At 5.8% bitumen content, the Marshall mix achieved the most desirable overall balance of strength, flexibility, and durability. It recorded the highest Marshall Stability of 1232.70 kg, which shows that the mix had strong load-carrying capacity and good internal cohesion at this binder level.

Figure 5: Laboratory Testing for Determination of Marshall Stability of RAP + RAS + Virgin Materials

The flow value of 3.27 mm at 5.8% was moderate, indicating that the mix was neither too stiff nor too plastic. This is important because a balanced flow value suggests the asphalt can resist cracking while still accommodating limited deformation under traffic loads.

The maximum density of 2.443 at 5.8% confirms that the mix attained the greatest compactness and densest packing at this binder content. Although the bulk specific gravity showed a slight overall decrease from 2.561 to 2.529, the change was small and

consistent, showing uniform mix behavior without major compaction issues.

The air void content of 3.99% at 5.8% was very close to the desirable 4% level, which indicates effective filling of void spaces by the binder. The VMA value of 14.19% was also at its minimum, showing efficient aggregate packing, while the VFB value of 71.89% confirmed that a suitable portion of the aggregate voids was filled with bitumen.

The Marshall Quotient of 3.77 at 5.8% further supports that the mix had a good balance between stiffness and deformation resistance. Overall, this binder content satisfied the MORTH requirements and was considered the optimum bitumen content for the developed recycled asphalt mix.

3.5 Compliance with MORTH Specifications

The Marshall test results were compared with the specified limits shown in the Marshall data sheet as per MORTH requirements, namely stability minimum 900 kg, flow 2–4 mm, air voids 3–5%, VMA minimum 13%, VFB 65–75%, and Marshall Quotient 2–5.

Table 5: Compliance of Marshall Parameters with MORTH Specifications

Bitumen Content (%)	Stability	Flow	Air Voids	VMA	VFB	Marshall Quotient	Overall Assessment
5.4	satisfy	satisfy	Does not satisfy	satisfy	Does not satisfy	satisfy	Partially satisfactory
5.6	satisfy	satisfy	Does not satisfy	satisfy	satisfy	satisfy	Satisfactory
5.8	satisfy	satisfy	satisfy	satisfy	satisfy	satisfy	Best satisfactory
6.0	satisfy	Does not satisfy	satisfy	satisfy	satisfy	satisfy	Partially satisfactory
6.2	satisfy	Does not satisfy	satisfy	satisfy	satisfy	Does not satisfy	Less satisfactory

The comparison indicates that the asphalt mix exhibited the most satisfactory overall performance at 5.8% bitumen content, because this level satisfied all the relevant Marshall requirements in a balanced manner.

3.6 Determination of Optimum Bitumen Content

The Optimum Bitumen Content (OBC) was determined on the basis of three standard Marshall mix design criteria: bitumen content corresponding to maximum Marshall Stability, bitumen content corresponding to maximum bulk specific gravity, and bitumen content corresponding to approximately 4 percent air voids. From the Marshall graphs and test data, all three criteria were satisfied at 5.8% bitumen content

Table 6: Determination of Optimum Bitumen Content

Criterion	Bitumen Content (%)
Bitumen content at maximum Marshall Stability	5.80
Bitumen content at maximum density & bulk specific gravity	5.80
Bitumen content at 4% air voids	5.80
Optimum Bitumen Content (OBC)	**5.80**

Thus, the Optimum Bitumen Content (OBC) of the developed asphalt mix was determined as 5.80%.

3.7 Marshall Properties at OBC: At the Optimum Bitumen Content of 5.8%, the Marshall and volumetric properties were taken as the final

performance indicators of the mix. These values showed the mix had good strength, compactness, void structure, and deformation resistance, confirming that the selected binder content was suitable for the developed asphalt mixture.

Table 7: Marshall Properties at Optimum Bitumen Content

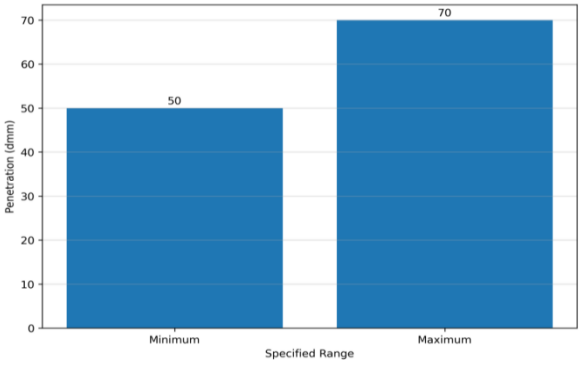
Property	Value at 5.8% Bitumen Content
Bulk Specific Gravity of Mix	2.443
Maximum Specific Gravity of Mix	2.545
Air Voids	3.99%
VMA	14.19%
VFB	71.89%
Stability	1232.70 kg
Flow	3.27 mm
Marshall Quotient	3.77

At 5.8% bitumen content, the mix showed the best overall performance. It recorded 1232.70 kg Marshall Stability, 2.443 bulk specific gravity, 3.99% air voids, 14.19% VMA, 71.89% VFB, 3.27 mm flow, and 3.77 Marshall Quotient, confirming good strength, compactness, and deformation resistanc

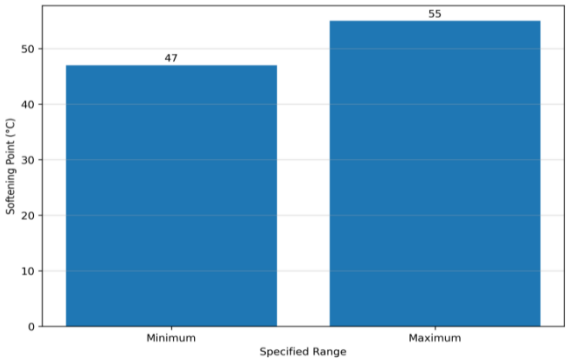
4. Result and Discussion

4.1 Results of VG-30 Bitumen Properties

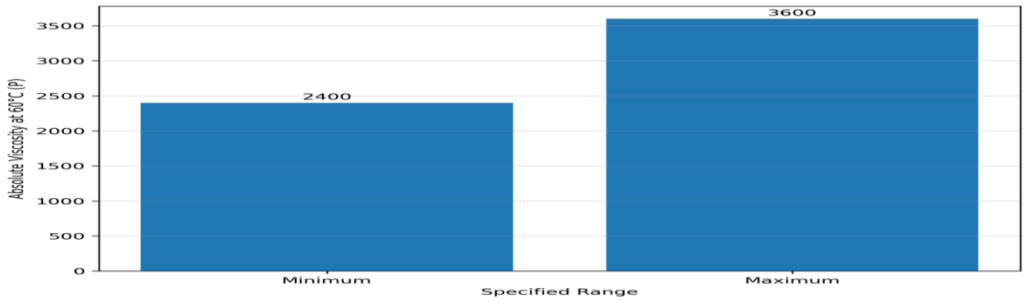
The basic properties of VG-30 bitumen considered in the present study were penetration, softening point, and absolute viscosity. These properties were examined to assess the suitability of the virgin binder before its use in the RAP + RAS modified asphalt mix. The laboratory photographs of viscosity, penetration, and softening point tests may be presented as Figure 6 (a), (b) & (c).



(a) Penetration range of VG-30 Bitumen



(b) Softening point range of VG-30 Bitumen



(c) Absolute viscosity range of VG-30 Bitumen

Figure 6: Analysis Viscosity, Penetration, and Softening Point Tests

The VG-30 bitumen properties were suitable for pavement use, with a penetration range of 50–70 mm, softening point of 47–55 °C, and absolute viscosity of 2400–3600 P at 60 °C. These values

confirm good consistency, temperature resistance, and workability for the RAP + RAS modified asphalt mix.

4.2 Results and Discussion of Final Mix Preparation and Evaluation

The final mix was prepared using RAP + RAS, virgin aggregates, lime filler, VG-30 bitumen, and rejuvenator, with a total binder content of 5.80%. Of this, 1.45% came from RAP, 1.88% from RAS, and 2.48% from virgin binder, showing effective use of reclaimed binder in the mix.

The gradation analysis showed that the combined aggregate blend remained within MORTH limits at all sieve sizes and closely followed the middle grading line. The highest positive deviation was at the 9.50 mm sieve, and the highest negative deviation was at the 0.300 mm sieve, but both were within the permissible range, confirming a well-graded and satisfactory mix.

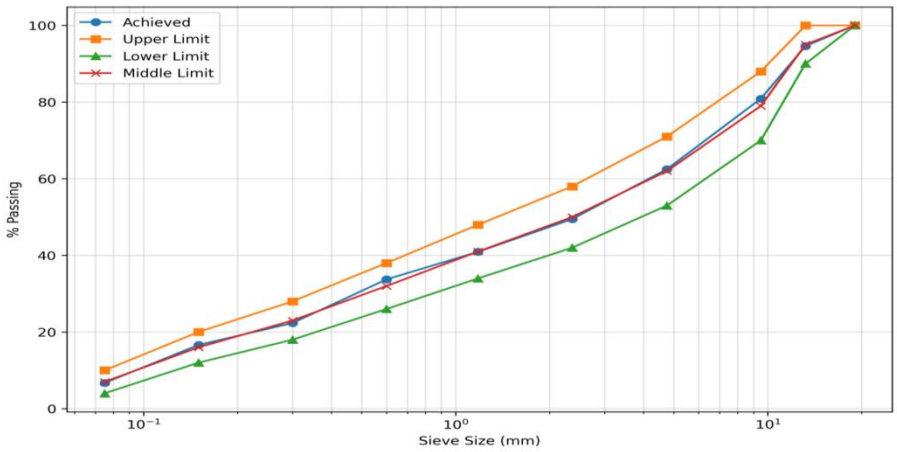


Figure 7: Combined aggregate gradation analysis curv of Final Mix

4.3 Results of Marshall Mix Design

The Marshall mix design was carried out at 5.4%, 5.6%, 5.8%, 6.0%, and 6.2% bitumen content to study the performance of the RAP + RAS modified asphalt mix. The results showed a clear trend that 5.8% was the most suitable binder content, as it provided the best balance of strength, compactness, void structure, and deformation resistance.

4.3.1 Marshall Stability: The Marshall Stability increased from 902.12 kg at 5.4% to 1071.74 kg at 5.6%, and reached a maximum of 1232.70 kg at 5.8%, before decreasing to 1008.38 kg at 6.0% and 905.33 kg at 6.2%. This indicates that stability improved as binder content increased up to 5.8%, due to better aggregate coating and cohesion, but declined beyond this point because excess bitumen reduced interlock.

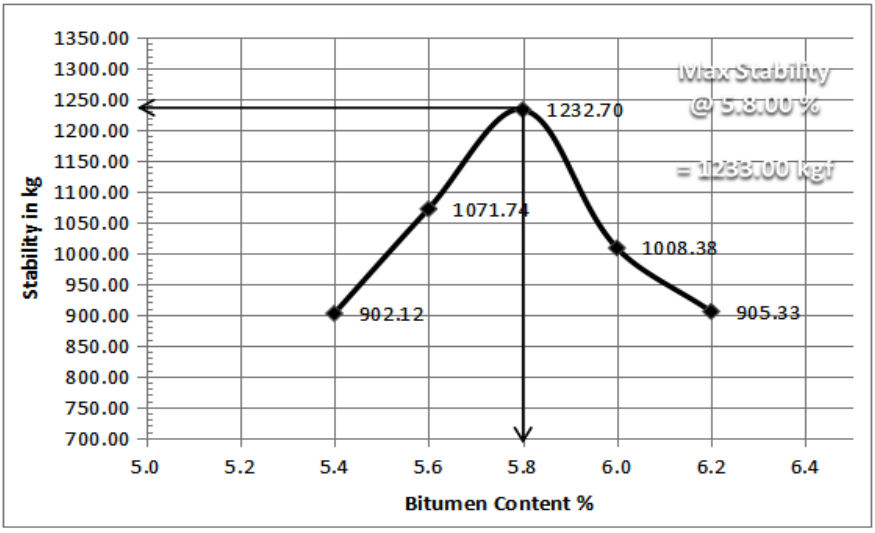


Figure 8: shows the variation of Marshall Stability with bitumen content

The maximum density increased from 2.388 at 5.4% to 2.443 at 5.8%, and then slightly decreased at higher binder contents. This shows that the mix achieved the highest compactness at 5.8% bitumen. In contrast, the maximum specific gravity decreased gradually from 2.561 at 5.4% to 2.529 at 6.2%, which is expected because bitumen has lower specific gravity than aggregates.

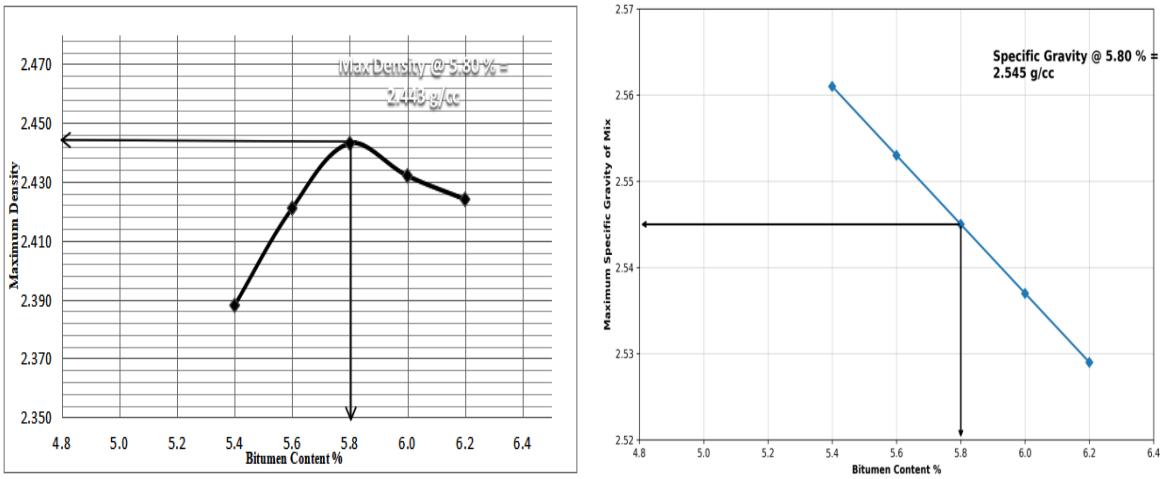


Figure 9: show the Maximum Density of the mix with bitumen content & variation of bulk specific gravity with bitumen content

The air voids decreased from 6.75% at 5.4% to 3.99% at 5.8%, then slightly changed at higher binder contents. The value of 3.99% at 5.8% is very close to the desirable 4%, showing a satisfactory void structure. The flow value increased steadily from 2.33 mm to 5.30 mm, indicating that the mix became more flexible with higher bitumen content, and the value at 5.8% remained within the acceptable range.

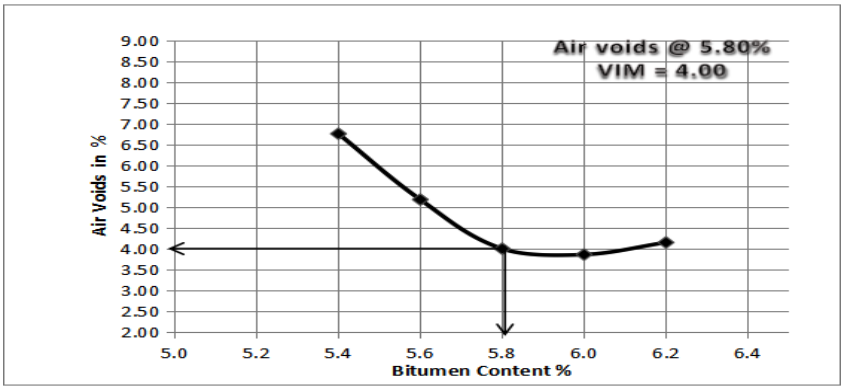


Figure 10: shows the variation of air voids with bitumen content

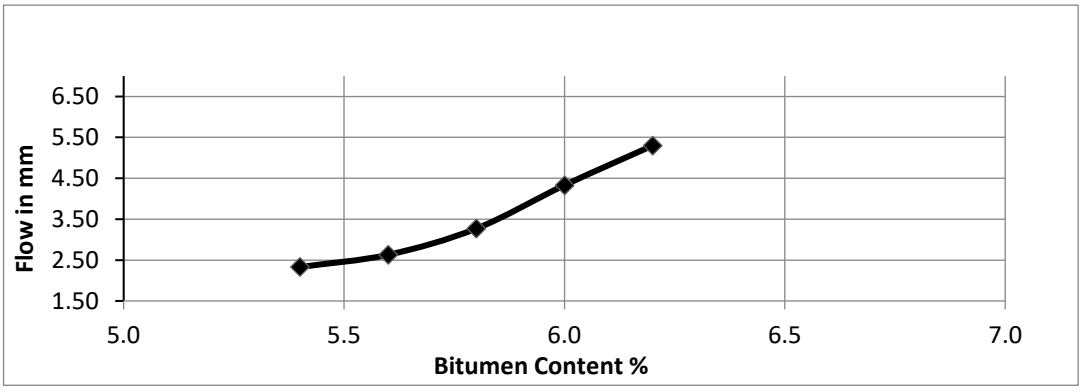


Figure 11: shows the variation of flow value with bitumen content

The VMA decreased from 15.77% at 5.4% to a minimum of 14.19% at 5.8%, then increased again. This means the aggregate particles were packed most efficiently at 5.8%. The VFB increased from 57.22% to 71.89% at 5.8%, showing that more void space was filled with binder, which supports durability and strength.

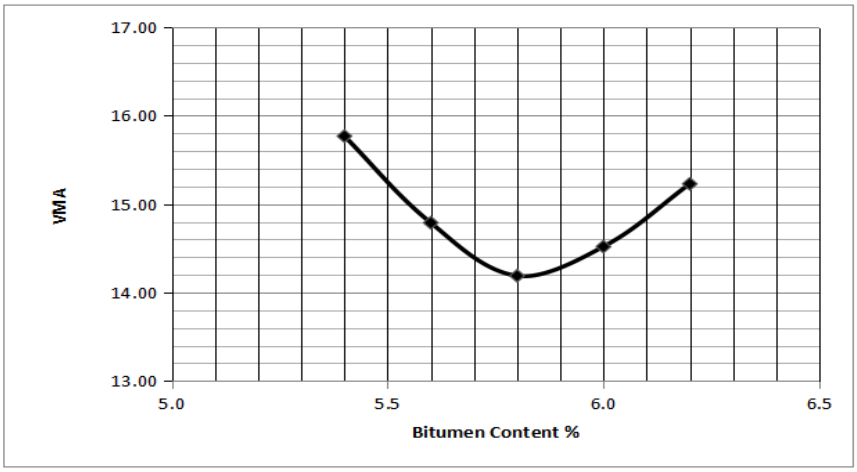


Figure 12: shows the variation of VMA with bitumen content

The VFB increased from 57.22% at 5.4% bitumen to 65.08% at 5.6%, 71.89% at 5.8%, and 73.49% at 6.0%, then slightly decreased to 72.80% at 6.2%. This shows that more void space was filled with binder as bitumen content increased, and the value at 5.8% was satisfactory for durability and strength.

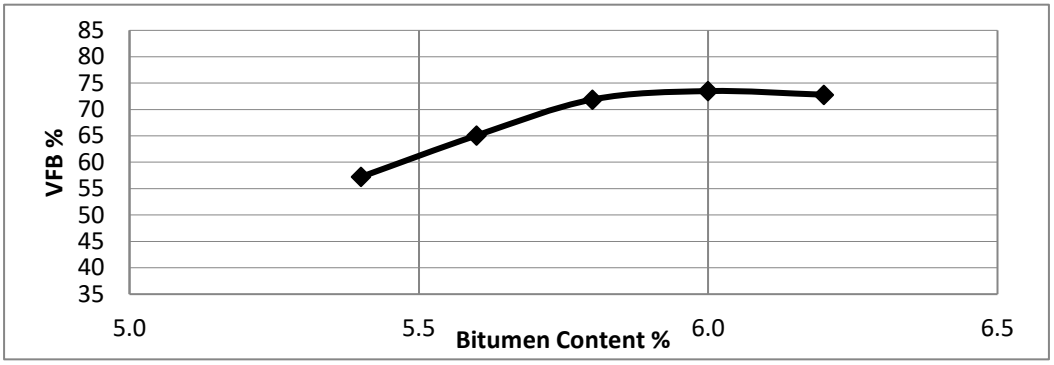


Figure 13: shows the variation of VFB with bitumen content

The Marshall Quotient values were 3.87, 4.07, 3.77, 2.32, and 1.71 for 5.4%, 5.6%, 5.8%, 6.0%, and 6.2% respectively. Although the highest value occurred at 5.6%, the value at 5.8% was still desirable and showed a good balance between stability and deformation resistance. Overall, the Marshall mix design confirmed that 5.8% bitumen content was the optimum binder level for the developed RAP + RAS modified asphalt mix.

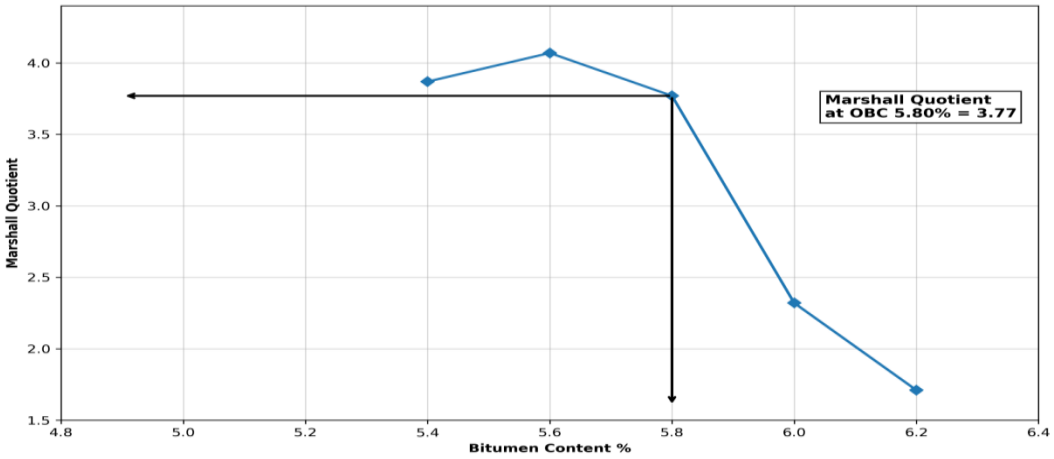


Figure 14: shows the variation of Marshall Quotient with bitumen content

Figure 15 shows that all three Marshall criteria converged at 5.8% bitumen content. At this binder level, the mix achieved maximum stability, maximum bulk specific gravity, and about 4% air voids, so the Optimum Bitumen Content (OBC) was fixed at 5.8%.

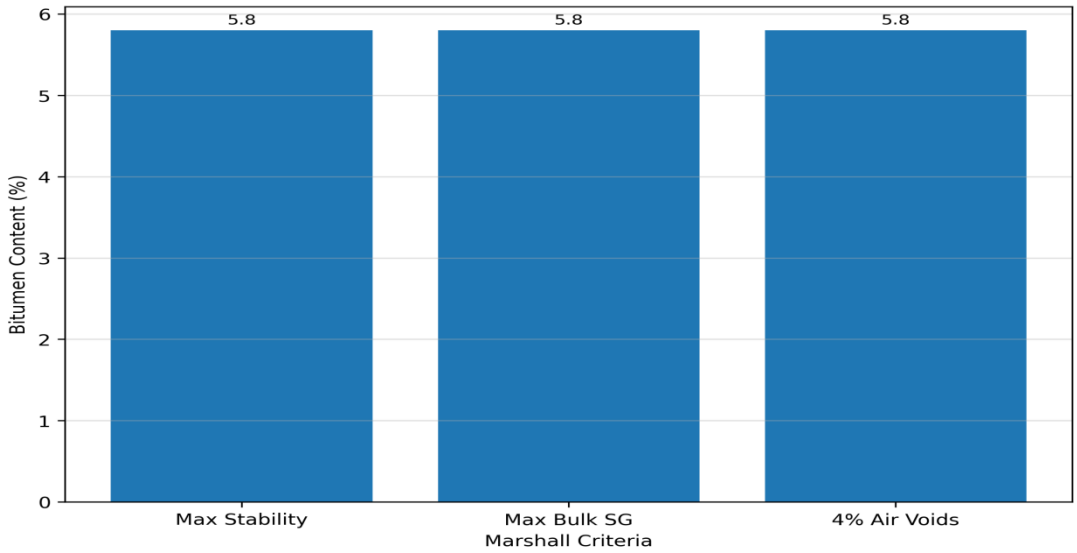


Figure 15: shows the determination of optimum bitumen content

5. Conclusion

This work concluded that RAP + RAS is technically feasible for hot mix asphalt when used with proper proportions of virgin aggregates, VG-30 bitumen, lime filler, and rejuvenator. The mix showed suitable binder properties, proper gradation within MORTH limits, and strong Marshall performance, with the Optimum Bitumen Content fixed at 5.8%.At this binder level, the mix achieved Marshall Stability of 1232.70 kg, bulk specific gravity of 2.443, air voids of 3.99%, flow value of 3.27 mm, VMA of 14.19%, VFB of 71.89%, and Marshall Quotient of 3.77. These values indicate a good balance of strength, compactness, flexibility, and resistance to deformation.The supporting performance tests also showed promising results, including rutting resistance of about 4.0 mm, fatigue life of about 700 cycles, and TSR of 0.80 or above. The addition of 1.94% lime improved moisture resistance and aggregate-binder adhesion, while the rejuvenator helped restore the performance of the aged binder.Overall, the developed RAP + RAS modified asphalt mix provided satisfactory structural and functional performance. This confirms its potential for sustainable pavement construction and effective reuse of recycled asphalt materials.

References

Federal Highway Administration. (2025). RAP: Recycling and sustainability. U.S. Department of Transportation.https://www.fhwa.dot.gov/pavement/recycling/rap.cfm

Recycled Materials Resource Center. (2014). Application of reclaimed asphalt pavement and recycled asphalt shingles in hot-mix asphalt: National and international perspectives on current practice. Transportation Research Board.https://onlinepubs.trb.org/onlinepubs/circulars/ec188.pdf

The Shingle Recycling Group. (2025). Guidelines for the use of reclaimed asphalt shingles in asphalt pavements.https://shinglerecycling.org/wp-content/uploads/2025/01/2019_03-Guidelines-for-Use-of-RAS-in-Asphalt-Pavements.pdf

Aurangzeb, Q., Al-Qadi, I. L., Abuawad, I. M., Pine, W. J., & Trepanier, J. S. (2012). Achieving desired volumetrics and performance for mixtures with high percentage of reclaimed asphalt pavement. Transportation Research Record, 2294(1), 34–42. https://doi.org/10.3141/2294-04

Behnood, A., & Modiri Gharehveran, M. (2019). Morphology, rheology, and physical properties of polymer-modified asphalt binders. European Polymer Journal, 112, 766–791. https://doi.org/10.1016/j.eurpolymj.2018.10.049

Bennert, T., Daniel, J. S., & Mogawer, W. (2014). Strategies for incorporating higher recycled asphalt pavement percentages: Review of implementation trials in northeast states. Transportation Research Record, 2445(1), 83–93. https://doi.org/10.3141/2445-10

Briere, R. (2000). Hot-mix asphalt paving handbook–2000. Transportation Research Board.

Ghabchi, R., Singh, D., Zaman, M., & Hossain, Z. (2016). Laboratory characterisation of asphalt mixes containing RAP and RAS. International Journal of Pavement Engineering, 17(9), 829–846. https://doi.org/10.1080/10298436.2015.1022778

Hand, A. J., & Aschenbrener, T. (2023). Case studies of practices and lessons learned when using reclaimed asphalt shingles in asphalt mixtures. Transportation Research Record, 2678(4), 719–731. https://doi.org/10.1177/03611981231186601

Hansen, K. R., & Newcomb, D. E. (2010). Asphalt pavement mix production survey on reclaimed asphalt pavement, reclaimed asphalt shingles, and warm-mix asphalt usage: 2009–2010. National Asphalt Pavement Association.

Mivehchi, M., Wen, H., Wen, Y., & Wang, L. (2022). Study of measures to design asphalt mixes including high percentages of recycled asphalt pavement and recycled asphalt shingles. Transportation Research Record, 2677(2), 869–879. https://doi.org/10.1177/03611981221108982

ASTM International. (2020). Standard test methods for chemical analysis of zinc yellow pigment (zinc chromate yellow) (ASTM D444-88, Reapproved 2020). https://www.astm.org

ASTM International. (2022). Standard test method for Marshall stability and flow of asphalt paving mixtures (ASTM D6927-22). https://www.astm.org

ASTM International. (2024). Standard test methods for quantitative extraction of asphalt binder content in asphalt mixtures (ASTM D2172/D2172M-17e1). https://www.astm.org