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Marshall Mix Design and Performance Evaluation of RAP RAS Modified Hot Mix Asphalt with Rejuvenator

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Abstract — The stiff aged binder contained in reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) can reduce the demand for virgin binder, but it may also limit workability and cracking tolerance. This study develops a dense-graded hot mix asphalt containing a combined 31.53% RAP and tear-off RAS, 0.50% rejuvenator, 1.94% hydrated lime, and VG-30 virgin bitumen. The aggregate blend was checked against the applicable Ministry of Road Transport and Highways grading envelope, and Marshall specimens were evaluated at total binder contents of 5.4, 5.6, 5.8, 6.0, and 6.2%. The measured responses included bulk and maximum specific gravity, air voids, voids in mineral aggregate, voids filled with bitumen, stability, flow, and Marshall quotient. All combined gradation values remained within the specified limits. Marshall stability increased from 902.12 kg at 5.4% binder to a maximum of 1232.70 kg at 5.8%, then decreased to 905.33 kg at 6.2%. At 5.8% binder, the mixture achieved a bulk specific gravity of 2.443, maximum specific gravity of 2.545, 3.99% air voids, 14.19% VMA, 71.89% VFB, 3.27 mm flow, and a Marshall quotient of 3.77 kN/mm-equivalent as reported from the adopted calculation basis. The convergence of maximum stability, maximum bulk density, and approximately 4% air voids established 5.8% as the optimum binder content. The results show that a properly graded RAP-RAS blend with a modest rejuvenator dosage can satisfy Marshall volumetric and strength requirements. Direct wheel-tracking, fatigue, moisture-susceptibility, and field validation are recommended before project-scale implementation.

Keywords— recycled asphalt shingles; reclaimed asphalt pavement; hot mix asphalt; Marshall stability; rejuvenator; optimum binder content

I. INTRODUCTION

Road construction consumes large quantities of mineral aggregate and petroleum-derived asphalt binder. Expansion and maintenance of highway networks intensify demand for these finite resources and increase the energy, emissions, and cost associated with quarrying, refining, and transportation. At the same time, reclaimed asphalt pavement and discarded asphalt roofing shingles represent binder-rich materials that can be returned to pavement production rather than placed in stockpiles or landfills. Their use therefore offers a practical route toward material circularity in asphalt construction.

RAS differs from conventional RAP because roofing shingles contain a comparatively high proportion of strongly aged asphalt, mineral granules, filler, and fibres. The recovered binder is generally much stiffer than virgin paving bitumen. This stiffness can improve resistance to permanent deformation, but excessive replacement or incomplete blending can reduce mixture workability and increase vulnerability to cracking. RAP presents a similar, though usually less severe, ageing challenge. Consequently, a combined RAP-RAS mixture cannot be designed solely by specifying a recycled-material percentage; the aggregate skeleton, total effective binder, volumetric response, strength, deformation, and need for binder softening must be considered together (Ghabchi et al., 2016; Ozer et al., 2013; Tapsoba et al., 2014).

Recycling agents or rejuvenators are used to restore part of the maltene fraction and reduce the brittleness of aged binder. Their effectiveness depends on chemistry, dosage, mixing conditions, and the extent to which virgin and recycled binders interact. A dosage that is too low may leave the mixture difficult to compact, whereas excessive softening can reduce rutting resistance. Laboratory optimization is therefore required to identify a balanced binder content and to establish whether a proposed recycled blend provides adequate load-carrying capacity without excessive flow (Arámbula-Mercado et al., 2018; Tran et al., 2017).

The Marshall method remains widely used for dense-graded asphalt mix design because it links stability and flow with density and void parameters. Although modern balanced mix design adds direct rutting and cracking tests, Marshall evaluation provides an appropriate first-stage screening tool where project laboratories and specifications are organized around conventional methods. For Indian highway applications, this approach is especially useful when combined aggregate gradation is verified against MoRTH limits and binder properties are checked against the relevant Indian Standards.

The objective of this study is to design and evaluate a RAP-RAS modified hot mix asphalt containing a low dosage of rejuvenator. Specifically, the work (i) characterizes the constituent blend, (ii) confirms aggregate gradation compliance, (iii) quantifies the effect of total binder content on Marshall stability, flow, density, and void parameters, and (iv) identifies the optimum binder content. The study focuses on directly measured Marshall and volumetric data and does not treat literature-derived or representative rutting, fatigue, or moisture values as experimental observations.

II. LITERATURE REVIEW

Early and subsequent studies consistently show that RAS increases mixture stiffness because its binder has undergone prolonged oxidation during manufacture and service. Ozer et al. (2013) reported improved high-temperature performance at high recycled binder replacement, while also emphasizing the need to control cracking. Tapsoba et al. (2014) similarly found that mixtures containing RAP and roofing shingles display a strong dependence on recycled-material content and temperature. These findings support the use of a performance-oriented design process instead of assuming that all recycled binder becomes fully active.

Ghabchi et al. (2016) compared laboratory mixtures containing different RAP and RAS proportions and found that the two recycled materials do not affect performance identically. RAS can provide strong rutting resistance, but increasing aged-binder contribution may adversely affect cracking resistance. Zieliński (2022) also highlighted the importance of dosage and mixture-level testing. The source of shingles, processing size, contamination control, and variability in binder content further influence consistency, particularly for tear-off shingles.

Rejuvenation is one strategy for recovering flexibility. Oldham et al. (2015) demonstrated the potential of bio-binders in wet-processed shingles, and Arámbula-Mercado et al. (2018) showed that both dosage selection and incorporation method affect high-RAP and high-RAS mixtures. Tran et al. (2017) reported that recycling agents can improve cracking-related performance, although dosage must be selected without eliminating the deformation resistance supplied by aged binder. Field work by Mokhtari et al. (2020) indicates that RAS-containing mixtures can be implemented successfully when mixture design and production are controlled.

Recent research continues to examine the combined effects of ageing and rejuvenation. Rejuvenator studies have shown that chemical compatibility and diffusion govern the restoration of binder properties, while sustainability assessments identify reductions in virgin-material consumption as a principal benefit (Fang et al., 2021; Iwama & Hayano, 2023). However, many published studies use Superpave, rheological, or advanced performance tests under material and climate conditions different from those encountered in India. The present investigation contributes a project-oriented Marshall dataset for a VG-30 mixture incorporating both RAP and tear-off RAS.

III. MATERIALS AND METHODS

1. Constituent Materials

The recycled fraction consisted of a combined RAP and tear-off scrap shingle material. The source blend supplied aged asphalt binder as well as mineral particles. Virgin aggregate was separated into nominal 13.2 mm and 6 mm fractions. Hydrated lime was added as mineral filler and to support aggregate-binder adhesion. VG-30 paving bitumen served as the virgin binder, and a liquid rejuvenator was introduced at 0.50% by total mixture mass to improve coating and workability of the aged-binder system.

Table 1: Constituent proportions in the final mixture

Material	Proportion by mass (%)	Function
RAP and RAS combined	31.53	Recycled aggregate and aged binder
Virgin aggregate 13.2 mm	19.89	Coarse aggregate
Virgin aggregate 6 mm	43.66	Fine aggregate
Hydrated lime	1.94	Mineral filler and adhesion support
VG-30 bitumen	2.48	Virgin binder contribution
Rejuvenator	0.50	Aged-binder softening and workability

Binder accounting indicated contributions of 1.45% from RAP, 1.88% from RAS, and 2.48% from virgin VG-30 binder, giving a total design binder content of 5.80% at the selected condition. The measured VG-30 properties were a penetration of 65 dmm, softening point of 52 °C, and absolute viscosity of 2650 P at 60 °C. These values were consistent with the adopted binder grade requirements.

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Figure 1: Actual laboratory testing of VG-30 bitumen used in the study

2. Aggregate Gradation

A combined gradation was developed by proportioning the recycled fraction, virgin aggregates, and lime. Sieve analysis was compared with the adopted MoRTH dense bituminous macadam grading envelope. Compliance at each sieve was used as a prerequisite for preparing Marshall specimens.

Table 2: Combined aggregate gradation and specification limits

Sieve size (mm)	Combined passing (%)	MoRTH limit (%)	Midpoint variation
19.0	100.00	100	0.00
13.2	94.63	90-100	-0.37
9.50	80.90	70-88	+1.90
4.75	62.49	53-71	+0.49
2.36	49.47	42-58	-0.53
1.18	40.93	34-48	-0.07
0.600	33.73	26-38	+1.73
0.300	22.34	18-28	-0.66
0.150	16.63	12-20	+0.63
0.075	6.71	4-10	-0.29

3. Marshall Specimen Preparation and Testing

Marshall specimens were prepared at total binder contents of 5.4, 5.6, 5.8, 6.0, and 6.2%. The aggregate and recycled materials were heated, blended with virgin binder and rejuvenator, and compacted in accordance with the adopted Marshall procedure. Stability and flow were determined following ASTM D6927, while bulk specific gravity and theoretical maximum specific gravity were obtained using the applicable AASHTO methods. Air voids, VMA, and VFB were calculated from the measured specific gravities and aggregate-binder proportions.

Air void content was evaluated from the relationship $V_a = 100(1 - G_{mb}/G_{mm})$, where Gmb is the bulk specific gravity of the compacted specimen and Gmm is the theoretical maximum specific gravity. This relationship was also used as an internal consistency check on the tabulated data. The optimum binder content was selected using the convergence of maximum stability, maximum bulk specific gravity, and approximately 4% air voids, followed by verification of flow, VMA, and VFB.

Figure 2: Actual preparation and Marshall testing of the RAP RAS asphalt mixture

IV. RESULTS AND DISCUSSION

1. Gradation Compliance

The combined blend satisfied the adopted grading limits at every sieve. The 19.0 mm sieve matched the required 100% passing value. The largest positive departure from the envelope midpoint was +1.90 percentage points at 9.50 mm, while the largest negative departure was -0.66 percentage points at 0.300 mm. The small deviations around the midpoint indicate that the blend followed the central grading line closely rather than accumulating near an upper or lower boundary. This condition supported stable particle interlock and reduced the likelihood that observed Marshall trends were caused by a poorly proportioned aggregate skeleton.

2. Marshall and Volumetric Response

Table 3: Marshall and volumetric test results

Binder (%)	Gmb	Gmm	Va (%)	VMA (%)	VFB (%)	Stability (kg)	Flow (mm)	MQ
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

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Stability increased by 36.6% between 5.4 and 5.8% binder, rising from 902.12 to 1232.70 kg. The increase reflects improved coating, cohesion, and compaction as binder content approached the optimum. Beyond 5.8%, stability decreased to 1008.38 kg at 6.0% and 905.33 kg at 6.2%. The post-peak reduction indicates that additional binder weakened aggregate interlock and promoted a more deformable mixture. The clear peak at 5.8% is therefore a stronger basis for selection than choosing a binder content merely because it produced acceptable compaction.

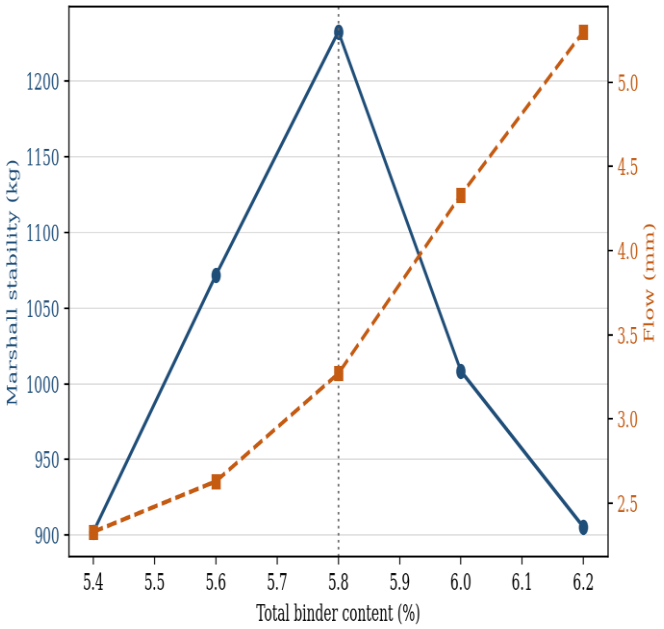

Figure 3: Effect of total binder content on Marshall stability and flow

Flow increased continuously from 2.33 mm at 5.4% to 5.30 mm at 6.2%. The 5.8% mixture produced a moderate flow of 3.27 mm alongside maximum stability. At higher binder contents, the rapid rise in flow and simultaneous decline in stability showed that the mixture was becoming excessively plastic. This inverse trend is also reflected by the Marshall quotient, which reached its maximum of 4.07 at 5.6% and then decreased to 3.77 at 5.8%, 2.32 at 6.0%, and 1.71 at 6.2%. Although the highest quotient occurred at 5.6%, that condition retained 5.17% air voids and did not provide the maximum density or stability. The 5.8% binder content offered the more balanced overall response.

Bulk specific gravity increased from 2.388 to 2.443 as binder content rose from 5.4 to 5.8%, then declined slightly. This density peak demonstrates that 5.8% binder most effectively filled accessible voids and supported compaction of the recycled aggregate structure. The theoretical maximum specific gravity decreased gradually with added binder, which is expected because the binder has a lower specific gravity than the mineral aggregate.

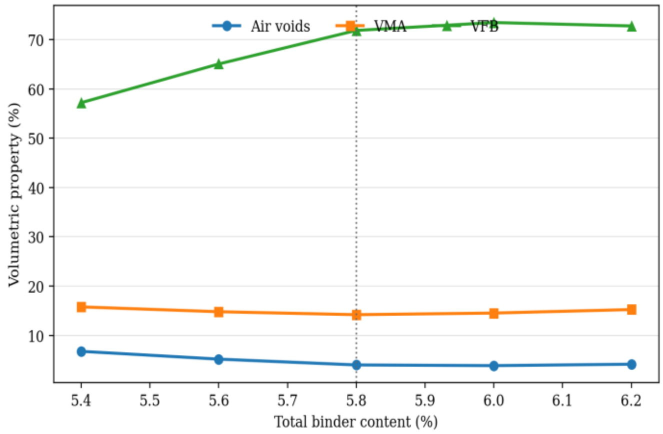

Figure 4: Effect of total binder content on volumetric properties

Air voids fell from 6.75% at 5.4% binder to 3.99% at 5.8%. This reduction confirms improved compactability and void filling. The small changes at 6.0 and 6.2% should be interpreted together with the loss in density and increase in flow; extra binder did not produce a stronger or denser structure. VMA declined to 14.19% at 5.8% and then increased, whereas VFB rose from 57.22% to 71.89% at the optimum and remained above 72% at the two higher binder contents. The combination of approximately 4% air voids, adequate VMA, and a non-excessive VFB at 5.8% supports the selected design point.

3. Selection of Optimum Binder Content

Table 4: Basis for selecting the optimum binder content

Selection criterion	Binder content identified (%)	Observation
Maximum Marshall stability	5.80	1232.70 kg
Maximum bulk specific gravity	5.80	Gmb = 2.443
Target air void content	5.80	Va = 3.99%
Flow and void verification	5.80	Flow = 3.27 mm; VMA = 14.19%; VFB = 71.89%

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All three primary selection criteria converged at 5.8% total binder content. This agreement is notable for a mixture containing 31.53% combined RAP and RAS because aged binder can complicate compaction and effective-binder estimation. The rejuvenator likely contributed to coating and mobility during compaction, while the lime and well-centered gradation supported a stable aggregate framework. However, the Marshall dataset alone cannot quantify how much RAS binder blended with virgin binder or determine long-term ageing and fracture behavior.

4. Comparison with Published Findings

The observed strength trend agrees with the broader literature showing that aged RAS and RAP binders can increase stiffness and high-temperature load resistance when the recycled fraction is properly controlled (Ghabchi et al., 2016; Ozer et al., 2013). The post-optimum reduction in stability and increase in flow also illustrate why additional binder or rejuvenator should not be assumed to improve all performance measures. Recycling-agent studies emphasize the need to balance restored flexibility with deformation resistance (Arámbula-Mercado et al., 2018; Tran et al., 2017).

The present results establish a satisfactory Marshall design but should be interpreted as screening evidence rather than proof of field durability. Published research identifies low-temperature and intermediate-temperature cracking as critical concerns for RAS mixtures, even when rutting resistance is strong (Shirzad et al., 2018; Tapsoba et al., 2016). Accordingly, direct wheel tracking, indirect tensile strength ratio, fatigue or semicircular-bend testing, and binder rheology should be completed before widespread adoption. This distinction is important because representative values taken from comparable literature cannot substitute for measurements on the developed mixture.

V. PRACTICAL IMPLICATIONS

The mixture replaces a substantial portion of virgin aggregate and binder-rich material with RAP and tear-off RAS. From a materials-management perspective, the design demonstrates that a combined recycled fraction above 30% can be incorporated while maintaining a compliant gradation and acceptable Marshall response. The use of only 2.48% virgin VG-30 binder in the final composition indicates potential for reducing virgin binder demand, although a complete economic or life-cycle claim requires local prices, haul distances, processing energy, and production emissions.

For plant implementation, recycled stockpiles should be source-controlled, protected from excess moisture, and processed to a consistent maximum size. RAS should be screened for deleterious materials, and its binder content should be measured routinely because small changes can materially alter total recycled binder contribution. Plant mixing time and temperature must allow uniform coating without accelerating further ageing. The 0.50% rejuvenator dosage should be treated as specific to the tested material combination rather than a universal dosage.

Limitations

The investigation used one combined RAP-RAS source, one virgin binder grade, and one rejuvenator dosage. Replicate-level variability was not available in the source dataset; consequently, inferential statistics and confidence intervals could not be reported. The proportions of RAP and RAS were accounted for through binder contribution, but separate mixture series isolating their individual effects were not tested. Furthermore, direct rutting, fatigue, cracking, moisture-susceptibility, dynamic modulus, ageing, and field-performance measurements were outside the verified experimental dataset. These limitations restrict the conclusions to Marshall mix design and volumetric suitability.

VI. CONCLUSIONS

- The combined aggregate blend containing RAP, tear-off RAS, virgin aggregates, and lime satisfied the adopted MoRTH grading limits at all sieve sizes.
- Marshall stability increased to a maximum of 1232.70 kg at 5.8% binder and declined at higher binder contents, demonstrating a distinct optimum rather than a continuously improving response.
- At 5.8% total binder, the mixture achieved Gmb of 2.443, Gmm of 2.545, 3.99% air voids, 14.19% VMA, 71.89% VFB, 3.27 mm flow, and a Marshall quotient of 3.77.
- Maximum stability, maximum bulk specific gravity, and approximately 4% air voids converged at 5.8%, establishing this value as the optimum binder content.
- The results support the laboratory feasibility of a mixture containing 31.53% combined RAP and RAS with 0.50% rejuvenator; however, project-scale use should follow direct balanced-performance and field validation.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

The data supporting the findings of this study are presented in the article. Additional laboratory records may be made available by the corresponding author on reasonable request.

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