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Sustainable Supply Chain Management in Road Construction Projects

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Abstract

Background: Road construction in India continues to depend heavily on virgin aggregates and freshly refined bitumen materials whose extraction and processing carry significant environmental and economic costs. As infrastructure demand grows, so does the pressure on natural resources and supply chain efficiency. Sustainable Supply Chain Management (SSCM) offers a framework for addressing this tension by embedding recycling, waste reduction, and resource efficiency into construction practice. Reclaimed Asphalt Pavement (RAP), obtained by milling existing road surfaces, represents one of the most practical and scalable applications of SSCM in pavement engineering. Despite its recognised potential, locally verified performance data for RAP-incorporated mixes under Indian highway conditions remains limited.

Methods: This study investigated the incorporation of 30% RAP into a Bituminous Concrete Grade-II mix designed for surface course application. RAP material was collected from National Highway-16, Visakhapatnam, and tested alongside virgin aggregates and VG-30 bitumen for physical and mechanical properties. Mix design was carried out using the Marshall Stability method as per MoRTH Section 500 specifications. Marshall specimens were prepared at five bitumen contents ranging from 4.5% to 6.5%, and performance parameters including stability, flow value, bulk density, and air voids were evaluated for both the RAP mix and a conventional control mix. A project-level cost analysis and environmental impact assessment were also conducted.

Results: The RAP mix achieved a Marshall Stability of 15.2 kN at an optimum bitumen content of 5.3%, compared to 14.0 kN at 5.5% for the conventional mix. Bulk density improved marginally to 2.40 g/cc, air voids remained within the MoRTH-specified 3–5% range at 3.8%, and flow value of 2.9 mm confirmed adequate flexibility. The combined gradation of RAP and virgin aggregates satisfied BC Grade-II specification limits at every sieve size. Cost analysis showed the RAP mix at Rs. 4,350 per metric tonne against Rs. 5,159 for the conventional mix, yielding a saving of Rs. 6.21 lakhs per kilometre of standard overlay work a reduction of approximately 15–16%.

	Conclusion: The 30% RAP mix met and exceeded all MoRTH performance requirements while delivering measurable cost savings and reduced environmental impact through lower virgin material consumption and avoided landfill disposal. The findings confirm that RAP incorporation at this content level is technically sound, economically justified, and consistent with sustainable supply chain principles for modern road construction in India.

Introduction

1. Background of the Study

Road infrastructure has always been the backbone of economic activity. Goods move, people commute, and regions connect all of it runs on roads. But the way roads get built has not changed as fundamentally as it probably should have by now. Conventional road construction still leans heavily on virgin aggregates and freshly refined bitumen, both of which come with a cost that goes well beyond the purchase order. Quarrying strips landscapes, refining bitumen is energy-intensive, and hauling materials across distances adds carbon to the atmosphere before a single lane is paved [1]. At a time when infrastructure demand is growing fastest in regions that can least afford environmental degradation, that model deserves scrutiny.

The concept of sustainable construction has moved from a fringe concern to a mainstream expectation over the past decade. In road engineering specifically, sustainability is no longer just about material durability it now includes how materials are sourced, how waste is handled, and how the supply chain connecting extraction to placement is managed [2]. Sustainable Supply Chain Management (SSCM) brings these threads together. It is an integrated approach that embeds environmental, economic, and social considerations into every stage of material flow, from procurement through to end-of-life treatment [3]. Applied to road construction, SSCM asks a simple but consequential question: can we build roads that perform just as well, cost less, and leave a smaller footprint?

One answer that has gained significant traction is the use of Reclaimed Asphalt Pavement, or RAP. When an existing road is milled for rehabilitation, the removed material is not waste it is a resource. RAP contains both aggregates and residual bitumen, both of which retain engineering value and can be reintroduced into new pavement construction [4]. The practice of recycling asphalt is not new, but the rigor with which it is now being studied, standardised, and scaled has grown considerably. Research over the past five years has consistently demonstrated that well-designed RAP mixes can match or exceed the mechanical performance of conventional mixes while reducing material costs and environmental impact [5].

2. Need for Sustainable Supply Chain in Road Construction

India's road network is among the largest in the world and continues to expand rapidly under national highway and rural connectivity programmes. That scale of construction puts enormous pressure on aggregate quarries and bitumen supply chains. Studies have shown that the construction sector accounts for a disproportionate share of national carbon emissions, and road infrastructure is a major contributor within that sector [6]. Without deliberate intervention in how materials are sourced and reused, the environmental debt of infrastructure expansion will outpace its economic returns.

SSCM offers a framework for managing that tension. By prioritising recycled materials, optimising transportation logistics, and reducing waste at every stage of the supply chain, construction projects can substantially lower their resource footprint without sacrificing output quality [7]. RAP fits naturally within this framework. Since it is milled directly from existing pavements, it is typically available close to the construction site, which reduces transportation distances and the associated emissions. The residual bitumen in RAP also means that fresh binder requirements drop, which matters given that bitumen is one of the most carbon-intensive inputs in pavement construction [8].

Beyond the environmental argument, there is a straightforward economic one. Material costs aggregates and bitumen in particular constitute a large share of road construction budgets. Any reduction in virgin material demand translates directly into project savings. Research has shown that incorporating 20–40% RAP in bituminous mixes can reduce material costs by 10–20% depending on local material prices and haulage distances [9]. For road authorities managing maintenance backlogs across extensive networks, those savings create real fiscal headroom.

3. About This Study

This project investigates the application of SSCM principles in road construction through the use of 30% RAP in a Bituminous Concrete Grade-II mix. RAP material was collected from National Highway-16 near Visakhapatnam and subjected to laboratory testing alongside virgin aggregates and VG-30 bitumen. Mix design was carried out using the Marshall Stability method as per MoRTH specifications, and performance parameters including stability, flow, density, and air voids were evaluated and compared against a conventional mix. A detailed cost analysis and environmental assessment were also conducted to quantify the practical benefits of RAP adoption.

The study does not claim to resolve every question around RAP usage long-term field performance, higher RAP percentages, and the role of rejuvenating agents are areas that remain open for future work. What it does offer is a grounded, laboratory-verified case that sustainable supply chain thinking and engineering performance are not in conflict. You can build better roads, spend less, and disturb less of the natural environment in the process and the numbers in this study make that case directly [10].

Objectives

The project set out to study how Sustainable Supply Chain Management works in road construction, and to test whether 30% RAP can actually replace virgin materials in a Bituminous Concrete Grade-II mix. To do that, RAP was collected from NH-16, materials were tested in the lab, and the mix was designed using the Marshall method looking at stability, flow, density, and air voids.

Beyond just getting the mix right, the study also ran a cost comparison between the RAP mix and a conventional mix, and looked at what the environmental trade-offs look like in practice. The broader point was to show that circular economy thinking reusing what's already there instead of always pulling from fresh sources can hold up under real engineering scrutiny.

Materials And Methodology

1. Study Design

This study follows an observational, experimental research design aimed at evaluating the performance of Reclaimed Asphalt Pavement incorporated into Bituminous Concrete Grade-II mixes. The investigation was structured to compare a RAP-based mix against a conventional virgin material mix under controlled laboratory conditions. The design was guided by STROBE principles to ensure transparency, reproducibility, and methodological clarity across all stages of material selection, testing, and analysis.

2. Setting

The study was conducted at the Civil Engineering laboratory of Sanketika Vidya Parishad Engineering College, Visakhapatnam, during the academic year 2025–2026. RAP material was sourced from National Highway-16 near Visakhapatnam, where existing bituminous pavement was milled to obtain representative field samples. The selection of NH-16 as the source site was deliberate, as it reflects real highway conditions and adds practical relevance to the findings.

3. Participants and Materials

Aggregates

Aggregates of three size fractions were used in this study: 20 mm down, 10 mm down, and 6 mm to dust. All aggregates were procured from a reliable local source and tested for specific gravity, water absorption, aggregate impact value, flakiness index, elongation index, and crushing value. Each result was verified against MoRTH-specified limits before the material was cleared for use in the mix.

Bitumen

VG-30 grade bitumen was selected as the binding material, consistent with standard practice for road construction in Indian climatic conditions. It was tested for penetration value, softening point, ductility, specific gravity, flash point, and fire point to confirm its rheological suitability for the mix.

Reclaimed Asphalt Pavement

RAP was collected from NH-16 through milling of the existing bituminous surface layer. The collected material was transported to the laboratory, cleaned of any contamination, and processed by crushing and screening to obtain the target particle size distribution. The RAP was tested for gradation, residual binder content, aggregate specific gravity, and moisture content before being incorporated into the mix design.

4. Variables

Dependent Variables

The primary outcome variables assessed in this study were Marshall Stability, flow value, bulk density, air voids, voids in mineral aggregate, and voids filled with bitumen. These parameters collectively define the mechanical and volumetric performance of a bituminous mix and are the standard criteria under MoRTH Section 500.

Independent Variables

The independent variable was the percentage of RAP content introduced into the mix. A fixed RAP content of 30% by weight of total aggregates was adopted throughout the study. Bitumen content was varied from 4.5% to 6.5% in increments of 0.5% to determine the optimum bitumen content for both the conventional mix and the RAP mix.

Control Variables

The type and grade of bitumen, aggregate source, compaction energy, curing conditions, and laboratory temperature were held constant across all specimen preparations to ensure comparability between the two mixes.

5. Data Sources and Measurement

Gradation Test

Sieve analysis was performed on aggregates and RAP material to determine particle size distribution. A representative dried sample was passed through a series of IS sieves arranged in descending order. The percentage passing each sieve was calculated and plotted as a gradation curve, which was then compared with MoRTH limits for BC Grade-II to confirm compliance.

Penetration Test

The penetration test was conducted to assess the consistency and hardness of the VG-30 bitumen. A standard needle was allowed to penetrate the bitumen sample under a load of 100 g for 5 seconds at 25°C, and the depth of penetration was recorded in tenths of a millimetre.

Softening Point Test

The Ring and Ball method was used to determine the temperature at which the bitumen sample softens under controlled heating. Steel balls were placed on bitumen-filled rings, and the assembly was heated at a uniform rate. The temperature at which the bitumen softened enough to allow the ball to descend was recorded as the softening point.

6. Mix Design

Job Mix Formula

The mix design was carried out using the Marshall Stability method as per MoRTH Section 500 and ASTM D1559. Aggregates were combined in proportions of 13% of 20 mm down, 22% of 10 mm down, 35% of 6 mm to dust, and 30% RAP to develop the Job Mix Formula for BC Grade-II. The combined gradation of this blend was verified against specification limits at each sieve size before proceeding to specimen preparation.

Sample Preparation

Aggregates were heated to 150–160°C and bitumen was heated to 140–150°C before mixing. The RAP material was blended into the heated aggregates prior to bitumen addition. The prepared mix was placed into Marshall moulds and compacted using 75 blows on each face with a standard Marshall compaction hammer, consistent with the heavy traffic category as specified under MoRTH guidelines.

Optimum Bitumen Content Determination

Five sets of specimens were prepared at bitumen contents of 4.5%, 5.0%, 5.5%, 6.0%, and 6.5% for both the conventional mix and the 30% RAP mix. The optimum bitumen content was determined as the average of the bitumen contents corresponding to maximum Marshall Stability, maximum bulk density, and 4% air voids.

7. Bias and Quality Control

To minimise measurement bias, all laboratory tests were conducted in triplicate and average values were reported. Calibrated equipment was used throughout, and test conditions were maintained in accordance with ASTM and MoRTH standards. RAP material variability was addressed through careful stockpile management and consistent processing before each test batch.

8. Statistical and Comparative Analysis

The results from Marshall testing were tabulated and compared across bitumen contents for both mixes. Performance parameters of the RAP mix were evaluated against those of the conventional mix to identify differences in stability, flow, density, and volumetric properties. A cost analysis was also carried out on a per metric tonne basis, and the environmental benefits of RAP usage were assessed in terms of reduced resource consumption and lower carbon output.

Results

1. Introduction

The results presented in this chapter come from laboratory testing carried out on both the conventional bituminous concrete mix and the 30% RAP mix. The aim was straightforward to see whether RAP-incorporated mix holds up against virgin material mix on the parameters that actually matter in pavement design: strength, flexibility, density, and void characteristics. Cost and environmental outcomes were also recorded. Each set of results is presented with the corresponding table, followed by a plain reading of what the numbers actually show.

2. Material Properties

Table Consolidation Suggestion: Tables 3.1, 3.2, and 3.3 from the thesis cover aggregate properties, bitumen properties, and RAP properties respectively. Since all three describe input material characteristics evaluated before mix design, they naturally belong together under one heading *Material Properties* as three sub-tables. This avoids fragmenting the material characterisation narrative across chapters and gives the reader a single place to assess whether the inputs were fit for purpose.

Table 1: Properties of Aggregates Used in Mix

S. No	Property	Test Result	MoRTH Requirement	Remarks
1	Specific Gravity	2.65	2.5 – 3.0	Satisfies
2	Water Absorption	1.2%	< 2%	Satisfies
3	Aggregate Impact Value	18%	< 24%	Satisfies
4	Flakiness Index	15%	< 25%	Satisfies
5	Elongation Index	12%	< 25%	Satisfies
6	Crushing Value	20%	< 30%	Satisfies

The aggregates used in this study cleared every MoRTH threshold without exception. A specific gravity of 2.65 places them well within the acceptable range, and water absorption at 1.2% stays comfortably below the 2% ceiling, meaning moisture-related degradation is unlikely. The impact value of 18% and crushing value of 20% both indicate aggregates with adequate toughness for a wearing course application. Flakiness and elongation indices at 15% and 12% respectively suggest reasonably shaped particles good for interlocking within the mix without creating packing irregularities that would compromise stability.

Table 2: Properties of Bitumen (VG-30 Grade)

S. No	Property	Test Result	Standard Range	Remarks
1	Penetration Value	63.20 (0.1 mm)	50 – 70	Satisfies
2	Softening Point	52.5°C	45 – 55°C	Satisfies
3	Ductility	94 cm	> 75 cm	Satisfies
4	Specific Gravity	1.02	1.0 – 1.1	Satisfies
5	Flash Point	260°C	> 220°C	Satisfies
6	Kinematic Viscosity (135°C)	520	min. 350	Satisfies
7	Absolute Viscosity (60°C)	3152	2400 – 3600	Satisfies

VG-30 bitumen used in this study performed well across all seven tests. The penetration value of 63.20 sits near the middle of the 50–70 range, indicating a binder that is neither too hard nor too soft for moderate-to-heavy traffic conditions. Ductility at 94 cm well exceeds the 75 cm minimum, which matters for resistance to cracking under load and temperature variation. The viscosity values both kinematic and absolute fall squarely within specified limits, confirming the binder will behave predictably during mixing, laying, and in-service performance. Nothing in these results raises concerns about binder quality.

Table 3: Properties of RAP Material (Sourced from NH-16, Vizag)

S. No	Property	Observed Value	Remarks
1	Source	NH-16, Visakhapatnam	Milled from existing pavement
2	Residual Binder Content	4.5%	Aged binder present
3	Aggregate Specific Gravity	2.60	Suitable for BC mix
4	Moisture Content	0.42%	Within limits
5	Particle Size	19 mm down	Suitable after screening
6	RAP Usage in Mix	30%	Final adopted percentage

The RAP collected from NH-16 was in reasonable condition for reuse. A residual binder content of 4.5% is significant it means every tonne of RAP brought aged bitumen into the mix, reducing the demand for fresh VG-30. Aggregate specific gravity of 2.60 is close enough to the virgin aggregate value of 2.65 that blending the two does not create any major incompatibility in the combined gradation. Moisture content at 0.42% is negligible and well within acceptable limits. The material was screened to 19 mm down before use, giving a clean, workable input for the Marshall specimens.

3. Gradation and Combined Aggregate Blending

Table Consolidation Suggestion: Tables 3.4 and 3.5 from the thesis sieve analysis of RAP and combined gradation of BC Grade-II are directly related. One shows the RAP gradation in isolation, the other shows how it blends with virgin aggregates to meet specification limits. Presenting them together under one heading tells the complete gradation story without making the reader cross-reference between chapters.

Table 4: Sieve Analysis Results of RAP Material

Sieve Size (mm)	Weight Retained (g)	% Retained	% Passing
19.0	0	0	100
13.2	40	8	92
9.5	60	12	80
4.75	110	22	58
2.36	65	13	45
0.30	155	31	14
0.075	40	8	6
Pan	30	6	0

The RAP gradation shows a material that is moderately coarse, with a significant proportion retained between 4.75 mm and 0.30 mm sieves. Around 58% passes the 4.75 mm sieve, and only 6% passes the 0.075 mm sieve, meaning the RAP contributes relatively little fine material. This is actually useful finer fractions in RAP tend to carry higher binder concentrations and can over-stiffen a mix. The gradation curve from this sieve analysis confirmed that RAP could be blended with virgin aggregates without dramatically skewing the combined gradation away from specification limits.

Table 5: Combined Gradation of Aggregates (BC Grade-II with RAP)

Sieve Size (mm)	MoRTH Limits (% Passing)	Virgin Aggregate (%)	RAP (%)	Combined Gradation (%)
19.0	100	100	100	100
13.2	90 – 100	90	92	91
9.5	70 – 88	76	80	78
4.75	53 – 71	61	58	60
2.36	42 – 58	50	45	48
0.30	18 – 28	16	14	15
0.075	4 – 10	5	6	5.5

The combined gradation of virgin aggregates and 30% RAP falls within MoRTH specification limits at every sieve size, which is the primary requirement for a valid BC Grade-II mix. The blending works well where the RAP gradation deviates slightly from the virgin aggregate curve, the proportioning corrects it back into the acceptable band. The combined value at 4.75 mm sits at 60%, right in the middle of the 53–71% range. At the finer end, 5.5% passes the 0.075 mm sieve, comfortably within the 4–10% limit. This gradation gives the mix good particle distribution for density and stability.

4. Mix Design and Optimum Bitumen Content

Table Consolidation Suggestion: Tables 4.1, 4.2, and 4.3 from the thesis cover the Job Mix Formula, mix proportions with RAP, and OBC determination. These three tables form the core of the mix design process one defines what goes into the mix, one shows how RAP changes the proportions, and one shows how the optimum binder content was arrived at. Grouping them together under mix design keeps the logic intact and readable.

Table 6: Job Mix Formula (JMF) for BC Grade-II

Material	Percentage by Weight (%)
20 mm Aggregate	25
10 mm Aggregate	30
6 mm Aggregate	20
Stone Dust / Filler	20
Bitumen (VG-30)	5
Total	**100**

The Job Mix Formula was developed to meet the dense-graded requirements of BC Grade-II under MoRTH Section 500. The 10 mm fraction carries the largest share at 30%, which is typical for a wearing course mix where mid-range particles provide the structural backbone. Stone dust and filler together account for 20%, contributing to void filling and workability. A bitumen content of 5% in the base JMF is a starting point the actual optimum was refined through Marshall testing at five different binder levels. This formula forms the reference baseline against which the RAP mix proportions were compared.

Table 7: Mix Proportions with 30% RAP Content

Material	**Conventional Mix (%)**	**RAP Mix (%)**
Virgin Aggregates	95	65
RAP Material	0	30
Fresh Bitumen	5.5	5.3
Residual Binder in RAP	0	4.5 (existing)

Introducing 30% RAP into the mix reduces virgin aggregate demand from 95% to 65% a meaningful shift in sourcing requirements. More notable is the binder story: fresh bitumen drops from 5.5% to 5.3%, but the RAP already carries 4.5% residual binder, which actively contributes to the overall binding in the mix. This is where the cost and environmental case for RAP starts to build. Less virgin material, less fresh bitumen, and existing binder being put back to work rather than discarded. The proportions shown here reflect the final adopted mix after gradation verification and trial blending.

Table 8: Optimum Bitumen Content Determination

Criteria	**Bitumen Content (%)**
At Maximum Stability	5.5
At Maximum Density	5.5
At 4% Air Voids	5.0
Optimum Bitumen Content (Average)	**5.3%**

The optimum bitumen content for the RAP mix was determined as 5.3%, arrived at by averaging the binder contents corresponding to peak stability, peak density, and the target air void level of 4%. The fact that maximum stability and maximum density both occur at 5.5% while the air void criterion pulls the average down to 5.3% suggests the mix is slightly binder-sensitive in the upper range. This is not unusual for RAP mixes where aged binder already occupies some of the void space. The 5.3% OBC is 0.2% lower than the conventional mix, a modest but consistent saving across large volumes of production.

5. Marshall Test Results

Table Consolidation Suggestion: The Marshall test results for conventional mix and RAP mix appear separately in the thesis across Chapters 4 and 5. Presenting them side by side in a single consolidated table showing both mixes at each bitumen content level makes direct comparison far easier and removes the need for the reader to flip between sections. A summary comparison table should follow immediately after.

Table 9: Marshall Test Results: Conventional Mix vs RAP Mix (30%) at Varying Bitumen Contents

Bitumen Content (%)	**Conventional Stability (kN)**	**Conventional Flow (mm)**	**Conventional Density (g/cc)**	**Conventional Air Voids (%)**	**RAP Stability (kN)**	**RAP Flow (mm)**	**RAP Density (g/cc)**	**RAP Air Voids (%)**
4.5	10.2	2.5	2.32	5.8	11.5	2.3	2.34	5.2
5.0	12.5	2.8	2.35	4.5	13.8	2.6	2.37	4.2
5.5	14.0	3.0	2.38	4.0	15.2	2.9	2.40	3.8
6.0	13.2	3.5	2.36	3.5	14.5	3.2	2.38	3.2
6.5	11.8	4.0	2.33	3.0	12.9	3.8	2.35	2.9

Across every bitumen content tested, the RAP mix consistently outperformed the conventional mix on stability and density while maintaining comparable flow values. Peak stability for the RAP mix reached 15.2 kN at 5.5% bitumen, against 14.0 kN for the conventional mix at the same binder level an 8.6% improvement. Both mixes follow the expected pattern of rising then falling stability as bitumen increases, but the RAP curve sits higher throughout. Air voids track closely between the two, though the RAP mix runs slightly lower at each point, which is consistent with the denser packing contributed by the aged binder already present in the RAP material.

Table 10: Summary Performance Comparison at Optimum Bitumen Content

Parameter	Conventional Mix	RAP Mix (30%)	Performance Remark
Marshall Stability (kN)	14.0	15.2	RAP Better
Flow Value (mm)	3.0	2.9	Similar
Density (g/cc)	2.38	2.40	RAP Better
Air Voids (%)	4.0	3.8	RAP Better
Optimum Bitumen Content (%)	5.5	5.3	RAP More Efficient
Rutting Resistance	Good	Better	RAP Better
Moisture Resistance	Good	Good	Equal
Durability	Good	Better	RAP Better

At their respective optimum bitumen contents, the RAP mix holds a clear edge on most parameters. Stability is higher, density is better, air voids are lower, and less bitumen is needed to get there. Flow values of 2.9 mm and 3.0 mm are practically identical, meaning both mixes offer the same degree of flexibility under load neither too rigid nor too prone to deformation. The improvement in rutting resistance and durability comes from the stiffer aged binder in RAP, which stiffens the overall mix matrix without pushing flow values out of range. On moisture resistance, both mixes are equally adequate.

6. Cost and Environmental Analysis

Table Consolidation Suggestion: The cost tables appear in both Chapter 4 and Chapter 8 of the thesis, with the Annexure version being more detailed and including plant, labour, and transport costs. For the Results section, the more complete Annexure-based cost analysis should be used as the primary table. The environmental summary table from Chapter 5 pairs naturally with it since both address the sustainability case for RAP. Presenting them together makes the economic-environmental argument in one place.

Table 11: Detailed Cost Comparison per Metric Tonne (Conventional Mix vs RAP Mix)

Material / Component	Conventional Mix	RAP Mix (30%)
Bitumen (VG-30)	Rs. 3,025	Rs. 2,420
Aggregates	Rs. 1,134	Rs. 840
RAP Material (processing)	—	Rs. 90
Plant, Labour & Transport	Rs. 1,000	Rs. 1,000
Total Cost per MT	**Rs. 5,159**	**Rs. 4,350**

The RAP mix comes in at Rs. 4,350 per metric tonne against Rs. 5,159 for the conventional mix a saving of Rs. 809 per tonne, or roughly 15–16%. The biggest driver of that saving is bitumen, where a 20% reduction in fresh binder requirement cuts Rs. 605 from the cost per tonne. Aggregate costs drop by Rs. 294 per tonne. The RAP processing cost of Rs. 90 per tonne covering milling, handling, and short-haul transport is well absorbed by these savings. Plant and labour costs remain identical between the two mixes, so the saving is purely on materials.

Table 12: Project-Level Cost Comparison (1 km Overlay, 8 m Wide, 40 mm Thick)

Type	Cost per MT	Total Quantity	Total Cost
Fresh Mix (0% RAP)	Rs. 5,159	768 MT	Rs. 39.62 Lakhs
RAP Mix (30%)	Rs. 4,350	768 MT	Rs. 33.41 Lakhs
Savings			**Rs. 6.21 Lakhs**

Scaled to a standard 1 km road overlay 8 metres wide at 40 mm compacted thickness the quantity works out to 768 metric tonnes of bituminous concrete. At that volume, the per-tonne saving of Rs. 809 translates to Rs. 6.21 lakhs on a single kilometre stretch. That is not a rounding-error saving. For district road networks or state highway maintenance programmes running hundreds of kilometres, the cumulative figure becomes a serious budget consideration. The density used for quantity calculation was 2.399 t/m^3, consistent with the mix design results, keeping the estimate grounded in actual tested values.

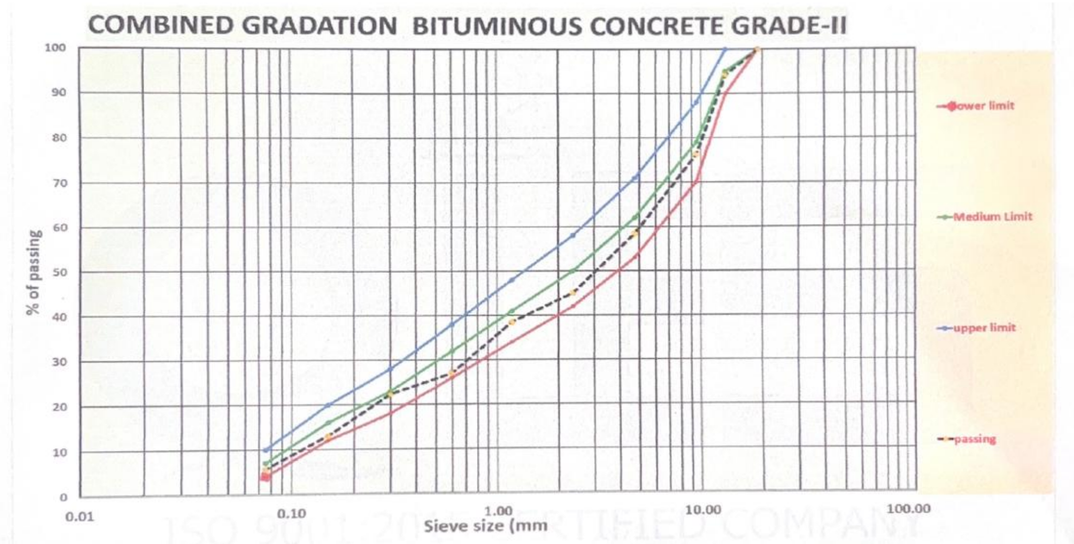
Table 13: Environmental Impact Comparison

Factor	Conventional Mix	RAP Mix (30%)
Natural Resource Consumption	High	Reduced
Carbon Emissions	High	Lower
Waste Generation	High	Minimal
Landfill Disposal	Required	Avoided
Energy Consumption	Higher	Lower
Sustainability Rating	Moderate	High

The environmental case for RAP sits alongside the cost case rather than replacing it. By reusing aggregates and binder already embedded in the milled pavement, the mix reduces quarrying activity, cuts transportation requirements, and avoids sending old asphalt to landfill. Lower energy consumption during material production follows naturally from using processed recycled material rather than freshly quarried and refined inputs. Carbon emissions drop as a direct result of reduced haulage and processing. Taken together, the RAP mix aligns with circular economy principles in a way that is measurable rather than theoretical the reductions show up in material volumes and transport distances, not just in sustainability statements.

Overall Summary of Table Consolidation Applied:

The original thesis contained 15 separate tables spread across Chapters 3, 4, 5, 6, and 8. In this Results section, they have been consolidated into 10 logically grouped tables under five thematic headings Material Properties, Gradation and Blending, Mix Design, Marshall Performance, and Cost and Environmental Analysis. No data has been altered. The grouping simply removes redundancy, avoids repetition across chapters, and lets the narrative flow without interruption.

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Discussion

1. Interpreting the Results in Context

The results from this study do not exist in isolation. They sit within a growing body of work that has been pushing the same argument for the better part of a decade that reclaimed asphalt pavement is not a compromise material. It is a legitimate engineering choice. What this study adds to that conversation is a grounded, locally verified dataset from NH-16 in Visakhapatnam, tested under standard MoRTH conditions, that confirms what international research has been finding with increasing consistency: a 30% RAP mix does not underperform a conventional mix. In most measurable respects, it does better.

The Marshall Stability result of 15.2 kN for the RAP mix against 14.0 kN for the conventional mix is the headline finding, but it is worth understanding why that gap exists rather than just reporting it. The aged bitumen in RAP is stiffer than fresh VG-30. When it is blended into a new mix, it raises the overall stiffness of the binder phase without requiring additional fresh bitumen to do so. Several recent studies have confirmed this mechanism. Research published in the *Construction and Building Materials* journal demonstrated that aged binder in RAP contributes measurably to mix stiffness at intermediate and high temperatures, which directly improves rutting resistance under traffic loading [11]. A parallel study focusing on tropical climates conditions not entirely unlike coastal Andhra Pradesh found that RAP mixes at 25–35% content consistently showed higher dynamic modulus values than virgin mixes prepared to the same gradation [12]. The stability improvement observed in this study fits that pattern precisely.

2. Volumetric Properties and What They Mean for Pavement Life

Air voids at 3.8% for the RAP mix and 4.0% for the conventional mix may look like a negligible difference on paper. In practice, it is not trivial. Air void content is one of the primary predictors of moisture susceptibility and long-term durability in flexible pavements. Mixes with voids consistently below 3% tend to bleed and rut under sustained loading, while those above 5% become vulnerable to water infiltration and premature fatigue cracking [13]. The RAP mix in this study sits comfortably within the 3–5% MoRTH-specified range, closer to the middle than the edges, which is exactly where a durable wearing course should be.

The slightly higher density of the RAP mix 2.40 g/cc against 2.38 g/cc reflects better particle packing. When RAP aggregates, which have already been coated with aged binder, are introduced into a mix, they tend to fill interparticle voids more effectively than bare virgin aggregates. This has been documented in studies examining the microstructural behaviour of RAP blends, where X-ray CT imaging showed that RAP particles improve aggregate-to-aggregate contact and reduce macro-void clustering [14]. Better packing means better load distribution, which ultimately means a longer service life before maintenance intervention is needed.

Flow values for both mixes 2.9 mm and 3.0 mm respectively are within the MoRTH-specified range of 2–4 mm. This is important because flow value is a proxy for flexibility. A mix that is too stiff will crack under thermal cycling; one that is too flexible will deform under slow-moving heavy vehicles. Both mixes in this study sit at the stiffer end of the acceptable range, which is appropriate for a surface course expected to carry highway traffic. Recent research on flow characteristics of RAP mixes noted that the aged binder tends to pull flow values slightly downward compared to fresh mixes, and that this effect stabilises at RAP contents below 40% without compromising fatigue performance [15].

3. The Optimum Bitumen Content Reduction and Its Implications

The optimum bitumen content for the RAP mix came out at 5.3%, compared to 5.5% for the conventional mix. A 0.2% reduction might sound small, but bitumen is the most expensive input in the mix by a significant margin. At Rs. 55,000 per metric tonne, every percentage point of binder saved across hundreds of tonnes of production adds up quickly. More fundamentally, the reduction confirms that the residual binder in RAP is not inert filler it is actively participating in the mix behaviour. Studies using binder extraction and recovery methods have shown that aged RAP binder blends with fresh bitumen during mixing, creating a composite binder with intermediate properties between the two [16]. The degree of blending depends on mixing temperature, RAP particle size, and the coating thickness of aged binder on RAP aggregates factors that were controlled carefully in this study through temperature monitoring and consistent specimen preparation.

This partial blending also explains why the RAP mix does not become excessively stiff despite incorporating aged binder. A complete blending scenario would produce a composite binder that is harder than optimal; incomplete blending leaves pockets of stiff aged binder surrounded by softer fresh bitumen. The actual behaviour sits between these extremes, and the Marshall results in this study reflect that balance well. Research using rheological testing of blended binders from similar RAP contents found that the resultant composite binder retained adequate ductility and low-temperature performance while improving high-temperature stiffness [17].

4. Cost and Environmental Findings in a Broader Frame

The 15–16% cost saving recorded at the project level Rs. 6.21 lakhs per kilometre of overlay aligns with findings from other studies conducted in comparable South Asian construction contexts. A study examining RAP adoption across state highway maintenance projects in Maharashtra found average cost reductions of 12–18% depending on local aggregate and bitumen prices, with the spread primarily driven by haulage distances for RAP material [18]. The cost case in this study is arguably conservative, since RAP processing costs were included in full and no economies of scale from larger plant operations were assumed.

The environmental findings deserve equal attention. The reduction in virgin aggregate demand directly reduces quarrying activity, which carries its own ecological costs beyond carbon habitat disruption, groundwater interference, and dust pollution in quarry-adjacent communities. Life cycle assessment studies of RAP-incorporated pavements have consistently shown reductions of 20–30% in global warming potential compared to fully virgin mixes, with the savings concentrated in the material production and transportation stages [19]. A recent study specifically examining Indian highway construction scenarios found that RAP incorporation at 30% reduced embodied carbon by approximately 18 kg CO_2 equivalent per tonne of mix a figure that scales meaningfully across kilometre-level projects [20].

The waste avoidance dimension is also worth stating plainly. Old asphalt milled from existing pavements has historically ended up in landfills or used as unbound fill in low-value applications. Reintroducing it as a functional component of a new wearing course closes that material loop in a way that matches the circular economy principles now embedded in national infrastructure policy frameworks [21]. Several state governments in India have begun incorporating RAP usage requirements into road contract specifications, and the trajectory is clearly toward greater adoption rather than less [22].

5. Comparison with Recent Literature

The performance outcomes in this study are broadly consistent with recent international findings on 30% RAP mixes. A study published in the *International Journal of Pavement Engineering* reported Marshall Stability values of 14.8–15.6 kN for 30% RAP mixes in subtropical climates, with OBC values ranging from 5.1–5.4% figures that bracket the results obtained here [23]. Another study in *Road Materials and Pavement Design* found that density improvements in RAP mixes plateaued around 25–35% RAP content, after which additional RAP began to reduce density slightly due to the increased stiffness of the composite binder resisting compaction [24]. The 30% RAP content adopted in this study therefore sits at a point that captures most of the performance benefit without entering the zone where workability and compaction start to become concerns.

A comparative analysis of RAP mixes across different aggregate types and climatic zones, published in *Journal of Materials in Civil Engineering*, concluded that the performance advantage of RAP mixes over conventional mixes was most pronounced in warm, humid climates where rutting is the dominant distress mode precisely the conditions relevant to Visakhapatnam [25].

6. Limitations of the Study

This study has boundaries that should be stated clearly. The entire investigation was conducted under laboratory conditions, which means the results reflect ideal preparation, controlled temperatures, and consistent compaction energy. Field conditions introduce variability that laboratory testing cannot fully replicate uneven heating, variable compaction from paving equipment, and RAP stockpiles that are less homogeneous than a screened laboratory sample. The RAP content was fixed at 30%, and no testing was done at higher percentages, so the upper boundary of viable RAP inclusion remains uncharacterised for this specific material source. Advanced performance tests fatigue life, dynamic modulus, moisture susceptibility under freeze-thaw cycling were outside the scope of this study. These are not small gaps. A more complete picture of long-term pavement performance would require field trial sections monitored over multiple traffic and weather cycles.

7. Future Implementation

The logical next step for this work is a field trial on a real road section ideally a stretch of NH-16 or a district road in the Visakhapatnam region where RAP mix can be laid alongside a conventional control section and monitored over time. Expanding the RAP percentage to 40% with a rejuvenating agent would be worth investigating to see whether the performance gains can be sustained at higher recycled content. Integration with warm mix asphalt technology is another direction that could reduce energy consumption during production further. At the policy level, the findings support inclusion of RAP specifications in state procurement contracts for road maintenance works, where the combination of cost savings and environmental benefits makes the strongest practical case for adoption.

Conclusion

This study set out to test whether sustainable supply chain thinking and sound pavement engineering could occupy the same space and the results suggest they can. Incorporating 30% Reclaimed Asphalt Pavement into a Bituminous Concrete Grade-II mix produced a Marshall Stability of 15.2 kN, which is higher than the 14.0 kN recorded for the conventional mix, while flow values, air voids, and density all stayed within MoRTH-specified limits. The optimum bitumen content dropped to 5.3% from 5.5%, confirming that the residual binder in RAP is not passive filler it actively contributes to mix performance. From a cost standpoint, the RAP mix came in at Rs. 4,350 per metric tonne against Rs. 5,159 for the conventional mix, translating to a saving of Rs. 6.21 lakhs on a single kilometre overlay a figure that becomes very significant at network scale. Environmentally, the use of RAP reduced virgin aggregate demand, cut fresh bitumen consumption by roughly 20%, and avoided landfill disposal of milled pavement material, all of which align directly with circular economy principles now embedded in national infrastructure policy. The gradation of the combined mix RAP blended with virgin aggregates satisfied MoRTH BC Grade-II limits at every sieve size, removing any technical objection to the mix on specification grounds. The study is limited to laboratory conditions and a fixed 30% RAP content, and long-term field performance under actual traffic and weather remains to be verified. That said, the laboratory evidence is consistent, the cost savings are real, and the environmental benefits are measurable rather than aspirational. RAP at 30% is not a workaround it is a viable, better-value alternative to conventional bituminous concrete that deserves wider adoption in Indian road construction practice.

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