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Optimization of Bituminous Mix Design Using Recycled Asphalt Pavement (RAP) And Bio-Based Additives

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***Abstract*— - As the demand for sustainable and eco-friendly construction materials continues to grow, this study explores an innovative approach to improving both the environmental footprint and durability of road infrastructure. Specifically, it investigates how combining Recycled Asphalt Pavement (RAP) with bio-based additives like algae and starch can create more resilient and sustainable bituminous mixes. RAP, which contains aged aggregates and binders reclaimed from existing asphalt layers, offers a promising alternative to virgin materials but often suffers from reduced flexibility and bonding capability. To address these issues, renewable additives are introduced—algae for its plasticizing effects and starch for its strength-enhancing properties. Through a series of laboratory tests, the research examines how these materials impact the physical, chemical, and mechanical performance of the mix, focusing on key factors such as stiffness, rutting resistance, fatigue life, and moisture susceptibility. Beyond performance, the study highlights significant environmental and economic benefits: reducing construction waste, conserving natural resources, lowering carbon emissions, and cutting material costs. Ultimately, this work aims to offer a practical, cost-effective, and sustainable solution for modern pavement construction, bridging the gap between engineering needs and environmental responsibility.**

***Index Terms*— Recycled Asphalt Pavement (RAP), flexible Pavement, Bio-based additives, Aggregate Replacement, mix design, Marshall test.**

I. INTRODUCTION

In this study, bituminous concrete mixes were developed using varying proportions of Reclaimed Asphalt Pavement (RAP) at 10%, 30%, and 50%. Specimens were prepared for each mix and tested for Marshall Stability to evaluate their structural integrity. The mix demonstrating the highest stability was further analyzed through Indirect Tensile Strength (ITS) testing to assess its resistance to cracking. Additionally, an economic analysis was conducted to estimate the potential cost savings associated with using RAP in pavement construction.

Asphalt recycling stands out as an effective and sustainable method for pavement rehabilitation, offering an alternative to conventional approaches such as overlaying or complete reconstruction. The process involves the reuse of aged asphalt material from deteriorated pavements, which can be partially or fully integrated into new mixes. When executed with proper design and quality control, asphalt recycling can deliver considerable long-term advantages. These include the conservation of non-renewable resources, reduction in construction waste and landfill usage, and significant energy savings. It also minimizes construction-related disruptions, enhances pavement smoothness, and reduces overall costs. Moreover, recycling allows for the optimization of material properties by adjusting aggregate gradation and binder content.

This approach is especially valuable in regions where high-quality materials are scarce or transportation distances are considerable. Notably, when properly engineered, recycled hot mix asphalt can match the performance of conventional mixes, making it a practical and environmentally responsible choice for modern road construction.

II. RESEARCH GAP

1. Most existing studies focus on low RAP content (typically below 30%), with limited data on the performance of higher RAP content (30%–50%) in bituminous concrete mixes.
2. There is a lack of integrated studies that correlate Marshall Stability results with other performance indicators like Indirect Tensile Strength (ITS) to assess long-term pavement performance.
3. Environmental benefits of RAP usage are frequently discussed qualitatively, with a shortage of quantitative assessments to support sustainability claims.
4. Many studies are conducted under controlled laboratory conditions, with limited emphasis on the practical applicability and scalability of RAP use in field conditions.

III. OBJECTIVES

1. To Design and preparation of bituminous mixes with varying percentages of RAP (10–50%) and bio-additives (2–10%). for achieving a balance between performance, cost-effectiveness, and environmental benefits.
2. To assess the effect of RAP and bio-additives on pavement performance parameters such as stability, fatigue resistance, rutting, and moisture susceptibility.
3. To provide insights into the feasibility of large-scale adoption of RAP and bio-additives in bituminous mix design.
4. Develop a test section using the optimized mix design and monitor performance under real-world conditions.
5. Assess environmental impacts, including resource conservation and reduction of carbon footprint. Perform life-cycle cost analysis for economic feasibility.

IV. METHODOLOGY

In this project, we are focused on designing a bituminous concrete (BC) mix suitable for use as a wearing course. The goal is to determine the appropriate quantities of bitumen and aggregates that satisfy both gradation and volumetric requirements, especially when incorporating reclaimed asphalt pavement (RAP).

The mix design process was conducted in two phases. Initially, virgin materials were used to develop a baseline mix using the Marshall Mix Design method was blended with virgin aggregates in varying proportions to meet the desired gradation for the BC mix.

The overall procedure involved four key steps: analysing the individual gradation of aggregates, replacing part of the virgin mix with RAP, preparing the test specimens, and conducting tests to evaluate their performance. (Prepare bituminous mixes with: **RAP content**: 10%, 20%, 30%, 40%, and 50%. **Bio-additives**: 2%, 4%, 6%, 8%, and 10% (by weight of binder).

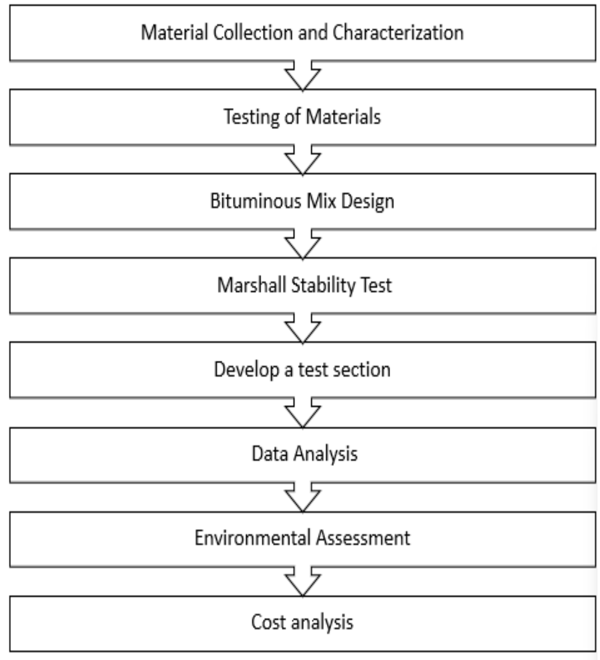

CHART NO.1

4.1. MATERIAL COLLECTION AND TESTING

- BITUMEN

Type: VG 30

- AGGREGATES

Size: 5-20 mm nominal size
Shape: Angular and crushed (Crushed Granite)
Specific gravity: 2.64

- RAP

Size Range: 5–20 mm
Specific gravity: 2.4 (by Pycnometer)
The Flaky Index is 10.46%. < 15 %
Elongation Index is 2.15%
Water Absorption: 1.5% – 3.0% (higher due to aged binder coating and micro-porosity)

Fig no :1 RAP

4.2. MIX DESIGN
For Bituminous mix the material

Binder Grade: VG-30
Optimum Bitumen Content: 5-6 %

Bitumen (VG-30)52
Coarse Aggregates 616.2
Fine Aggregates 331.8
Total Mix: 1000 kg

Bitumen %	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (Kg)	Flow
5	2.370	2.461	4.58	11.96	16.54	72.31	1452.48	3.7
5.2	2.367	2.443	4.12	13.12	17.24	76.11	1549.30	3.9
5.5	2.364	2.462	3.3	14.32	17.62	81.26	1394.38	4.4
6	2.362	2.410	2.44	15.53	17.97	86.4	1268.49	5.5

Table no:1 Marshall Test Results for Virgin Specimen

From the tests carried out by various percentage bitumen contains above results shows that optimum bitumen contain is 5.2%

Optimum Bitumen Content: 5.2%

(IS code referred for mix design are IRC:SP:135-2022, IRC:105-1988, IS:2720, IS: 1206)

4.3. MIX DESIGN WITH 10% REPLACEMENT
Mix Proportions (for 1000Kg with 10% RAP replacement by WEIGHT):

1. Replace 10% of aggregate weight with RAP:
    1. RAP = 10% of 945 = 94.5 kg.
    2. Virgin Aggregates = 945 - 94.5 = 850.5 kg.
2. Divide virgin aggregate weight among coarse aggregates, fine aggregates, and filler:
    1. Coarse Aggregate (60% of 850.5) = 510.3 kg.
    2. Fine Aggregate (30% of 850.5) = 255.2 kg.
    3. Mineral Filler (10% of 850.5) = 85.0 kg.

4.4 MIX DESIGN WITH 20% REPLACEMENT
Mix Proportions (for 1000Kg with 20% RAP replacement by weight):

1. Replace 20% of Aggregate Weight with RAP:
    1. RAP = 20% of 945 = 189 kg.
    2. Virgin Aggregates = 945 - 189 = 756 kg.
2. Distribute Virgin Aggregate Weight:
    1. Coarse Aggregate (60% of 756) = 453.6 kg.
    2. Fine Aggregate (30% of 756) = 226.8 kg.
    3. Mineral Filler (10% of 756) = 75.6 kg.

4.3 MIX DESIGN WITH 30% REPLACEMENT
Mix Proportions (for 1000Kg with 30% RAP replacement by weight):

1. Replace 30% of Aggregate Weight with RAP:
    1. RAP = 30% of 945 = 283.5 kg.
    2. Virgin Aggregates = 945 - 283.5 = 661.5 kg.
2. Distribute Virgin Aggregate Weight:
    1. Coarse Aggregate (60% of 661.5) = 396.9 kg.
    2. Fine Aggregate (30% of 661.5) = 198.45 kg.
    3. Mineral Filler (10% of 661.5) = 66.15 kg.

4.4 MIX DESIGN WITH 40% REPLACEMENT
Mix Proportions (for 1000Kg with 40% RAP replacement by weight):

1. Replace 40% of Aggregate Weight with RAP:
    1. RAP = 40% of 945 = 378 kg.
    2. Virgin Aggregates = 945 - 378 = 567 kg.
2. Distribute Virgin Aggregate Weight:

1. Coarse Aggregate (60% of 567) = 340.2 kg.
2. Fine Aggregate (30% of 567) = 170.1 kg.
3. Mineral Filler (10% of 567) = 56.7 kg.

4.5 MIX DESIGN WITH 50% REPLACEMENT

Mix Proportions (for 1000Kg with 50% RAP replacement by weight):

1. Replace 50% of Aggregate Weight with RAP:
    1. RAP = 50% of 945 = 472.5 kg.
    2. Virgin Aggregates = 945 - 472.5 = 472.5 kg.
2. Distribute Virgin Aggregate Weight:
    1. Coarse Aggregate (60% of 472.5) = 283.5 kg.
    2. Fine Aggregate (30% of 472.5) = 141.75 kg.
    3. Mineral Filler (10% of 472.5) = 47.25 kg.

V. TESTS

5.1. BITUMEN TESTING

These tests assess the properties of bitumen

Property	Test	Obtained Value	Specifications
Hardness & Softness	Penetration Test	23 mm	50mm
Ductility	Ductility Test	68 cm	50mm
Flow Resistance/ Consistency	Viscosity Test	87 sec	< 1min
Safety	Flash & Fire Point Test	174oC & 243oC	220 oC
Thermal Sensitivity	Softening Point Test	53 oC	47 oC
Packing of Particles	Specific Gravity Test	1.02	

Table no:2 Results of Bitumen Test

5.2 DUCTILITY TEST OF BITUMEN

Objective: To measure the extent to which bitumen can stretch before breaking – an indicator of its elastic and adhesive properties.

Fig no :2 Ductility Test

5.3. PENETRATION TEST OF BITUMEN

Objective: To measure the hardness or softness of bitumen by determining the depth a standard needle penetrates into the sample under specific conditions.

Fig no :3 Penetration Test

5.4 MARSHALL STABILITY AND FLOW TEST

Purpose: To determine the stability (resistance to deformation) and flow (deformation under load) of the bituminous mixture.

Significance: Assesses the overall strength, durability, and performance of the mix under typical traffic loads.

Fig no :4 Bitumen Mould

Fig no :5 Marshall Test

5.5 MOISTURE SUSCEPTIBILITY TEST

Purpose: To evaluate the moisture resistance of the mix, which is essential for preventing stripping or loss of binder adhesion due to water.
Significance: Ensures the mixture's durability in moist environments and evaluates the effectiveness of bio-based additives in improving moisture resistance.

Fig no :6 Moisture Susceptibility Tests

VI. RESULTS

6.1 MARSHALL TEST RESULTS FOR VIRGIN SPECIMEN

Bitumen %	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (Kg)	Flow
5	2.370	2.461	4.58	11.96	16.54	72.31	1452.48	3.7
5.2	2.367	2.443	4.12	13.12	17.24	76.11	1549.30	3.9
5.5	2.364	2.462	3.3	14.32	17.62	81.26	1394.38	4.4
6	2.362	2.410	2.44	15.53	17.97	86.4	1268.49	5.5

Table no:3 Marshall Test Results for Virgin Specimen

6.2 MARSHALL TEST RESULTS FOR 10% RAP

The bitumen mix of 10% RAP replacement and Bio-additives(starch): 2%, 4%, 6%, 8%, and 10% (by weight of binder).

Bitumen (+biobased additives)	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (KN)	Flow
66	2.279	2.445	6.81	0.12	6.93	1.69	10.3	3.7
64.68+1.32	2.307	2.511	8.12	0.12	8.24	1.46	11.43	3.9
63.36+2.64	2.32	2.493	6.94	0.12	7.06	1.69	11.73	3.75
62.04+3.96	2.332	2.475	5.78	0.12	5.9	2.01	11.5	3.5

60.72+5.28	2.328	2.457	5.27	0.12	5.39	2.21	10.83	3.7
59.04+6.60	2.314	2.441	5.22	0.12	5.34	2.22	10	3.62

Table no:4 Marshall Test Results for 10% RAP

6.3 MIX PROPERTIES FOR 20% RAP

The bitumen mix of 20% RAP replacement and Bio-additives(starch): 2%, 4%, 6%, 8%, and 10% (by weight of binder).

Bitumen (+ biobased additives)	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (KN)	Flow
66	2.326	2.441	4.74	0.12	4.86	2.6	10.5	3.78
64.68+1.32	2.35	2.511	6.39	0.12	6.51	1.87	11.3	3.8
63.36+2.64	2.358	2.493	5.23	0.12	5.35	2.22	11.6	3.95
62.04+3.96	2.363	2.475	4.44	0.12	4.56	2.59	10.6	3.72
60.72+5.28	2.366	2.457	3.7	0.12	3.82	3.01	10.55	3.48
59.04+6.60	3.348	2.445	3.97	0.12	4.09	2.96	10.1	3.37

Table no:5 Marshall Test Results for 20% RAP

6.4 MIX PROPERTIES FOR 30% RAP

The bitumen mix of 30% RAP replacement and Bio-additives(starch): 2%, 4%, 6%, 8%, and 10% (by weight of binder).

Bitumen+Bio Based Additives (gm)	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (KN)	Flow
66	2.329	2.445	4.77	0.12	4.89	2.53	10.85	4.02
64.68+1.32	2.361	2.511	5.98	0.12	6.1	2	11.5	3.85
63.36+2.64	2.367	2.493	5.05	0.12	5.17	2.33	11.4	3.725
62.04+3.96	2.371	2.466	3.87	0.12	3.99	3.1	11.35	3.725
60.72+5.28	2.364	2.461	3.97	0.12	4.09	3.01	10.65	3.485
59.04+6.60	2.364	2.443	3.25	0.12	3.37	3.58	10.1	3.37

Table no:6 Marshall Test Results for 30% RAP

6.5 MIX PROPERTIES FOR 40% RAP

The bitumen mix of 40% RAP replacement and Bio-additives(starch): 2%, 4%, 6%, 8%, and 10% (by weight of binder).

Bitumen+Bio Based Additives (gm)	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (KN)	Flow
66	2.329	2.445	4.77	0.12	4.89	2.53	10.08	4.4
64.68+1.32	2.361	2.511	5.98	0.12	6.1	2	10.01	3.8
63.36+2.64	2.367	2.493	5.05	0.12	5.17	2.33	10.3	3.7
62.04+3.96	2.371	2.466	3.87	0.12	3.99	3.1	11.3	3.2
60.72+5.28	2.364	2.461	3.97	0.12	4.09	3.01	10.65	3.85

59.04 +6.60	2.364	2.443	3.25	0.12	3.37	3.58	10.1	3.7

Table no:7 Marshall Test Results for 40% RAP

6.6 MIX PROPERTIES FOR 50% RAP

The bitumen mix of 50% RAP replacement and Bio-additives(starch): 2%, 4%, 6%, 8%, and 10% (by weight of binder).

Bitumen+ Bio Based Additives (gm)	Bulk density (gm/cc)	Theoretical density (gm/cc)	Vv %	Vb %	VMA %	VFB %	Stability (KN)	Flow
66	2.329	2.445	4.77	0.12	4.89	2.53	9.7	5.5
64.68 +1.32	2.361	2.511	5.98	0.12	6.1	2	10.02	5.8
63.36 +2.64	2.367	2.493	5.05	0.12	5.17	2.33	9.8	5.85
62.04 +3.96	2.371	2.466	3.87	0.12	3.99	3.1	9.57	5.2
60.72 +5.28	2.364	2.461	3.97	0.12	4.09	3.01	9.5	5.7
59.04 +6.60	2.364	2.443	3.25	0.12	3.37	3.58	9.38	5.5

Table no:8 Marshall Test Results for 50% RAP

VII.TEST SECTION

1. Test Section Parameters

Parameter	Value	Notes
Length of Road Section	100 m	Test stretch
Width of Road	7.0 m	2-lane width
Thickness of Layer	0.10 m (100 mm)	Wearing + binder
Density of Compacted Mix	2.35 t/m³	Standard field value
Wastage Allowance	2%	Site handling loss

Table no:9 Test Section Parameters

2.Material Requirement For 100m

Material	Quantity (Tonnes)
VG30 Bitumen	8.73
RAP (Reclaimed Material)	67.12
Corn Starch (Bio Additive)	10.07
Virgin Aggregates	81.88
Total Bituminous Mix	167.8

Table no:10 Material Requirement

Fig no :7 Test Section

Fig no :7 Test Section

VIII.COST ASSESSMENT

- The **modified mix costs ~₹1.05 lakh** more than the conventional one for a 100 m section — an increase of around **18.9%**.
- The main driver of added cost is the **bio-based additive (corn starch)**.
- Bitumen and virgin aggregate savings reduce some of this cost burden.
- RAP helps lower costs but adds **handling and processing cost**.
- The long-term **durability**, **recyclability**, and **carbon credit potential** of the modified mix can **offset the initial cost increase**.

- Additionally, if the **corn starch is locally sourced or subsidized**, the total cost could fall closer to parity.

Cost Item	**Conventional (INR)**	**Modified (INR)**	**Difference (INR)**	**Impact**
VG-30 Bitumen	₹525,800	₹480,150	**-₹45,650**	Saving
Virgin Aggregates	₹158,240	₹81,880	**-₹76,360**	Saving
RAP Material	₹0	₹33,560	**+₹33,560**	Cost
Corn Starch Additive	₹0	₹251,750	**+₹251,750**	Cost
Production, Transport, Laying	₹201,360	₹205,555	**+₹4,195**	Neutral
Total Project Cost	₹885,400	₹1,052,895	**+₹167,495**	↑ 18.9%

Table no:10 Cost Comparison

IX. ENVIRONMENTAL ASSESSMENT

The environmental assessment of the 100-meter test road constructed using **5.2% VG-30 bitumen**, **40% RAP**, and **6% corn starch additive** clearly demonstrates significant sustainability advantages over conventional pavement practices. Key benefits include:

- **67 tonnes of RAP** reused, reducing landfill use and natural resource extraction.
- **~10 tonnes of renewable corn starch additive** introduced, replacing petroleum-based modifiers.
- **~8.7 tonnes of bitumen** used—less than standard mixes—cutting carbon emissions.
- **Up to 25 tonnes of CO_2-equivalent emissions saved** in a 100 m section.
- **50+ GJ of energy saved** during mix production and material sourcing.

X. CONCLUSION

1.Stability Performance:
From the Marshall tests carried out the results shows that the stability of 40% replacement RAP with 6% Bio-based additives (starch) is optimistic replacement of aggregate for flexible pavement.

2.Mechanical Properties and Durability:
Although there was a gradual decrease in **stability and flow** with increasing RAP content, and bio-based additives mixes with up to **10–50% RAP** and 2-10% Bio-based additive (Starch) retained sufficient mechanical strength for pavement applications.

3.Optimal Replacement and Climate Consideration:
The performance across varying RAP levels suggests that **40% RAP** with 6% Bio-based additive (Starch) is suitable in most climates, especially where **flexibility, thermal stress resistance, and sustainability** are priorities.

4.Environmental Benefits: The reuse of RAP in pavement has **significant environmental advantages**, including:

- Diverting waste from landfills,
- Reducing the demand for virgin aggregates,
- Lowering the carbon footprint of pavement production.

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