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Revolutionizing Marshall Mix Design: Sustainable Integration of Recycled Aggregates Partially in Hot-Mix Asphalt Concrete

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Abstract: This study explores the use of recycled aggregates (RA) in Dense Bituminous Macadam (DBM) through the Marshall Mix method. Five mixes were evaluated: 100% natural aggregates (NA) and four blends with 25%, 50%, 75%, and 100% RA. Marshall Properties, stripping, drain down, & indirect tensile strength (ITS) tests were performed. The optimum binder content (OBC) ranged from 4.5% to 4.72%, meeting the MoRTH minimum of 4.5%. Air voids decreased with more RA but stayed within 3%–5%. VMA values were above 13%, and VFB ranged from 69.24% to 75%, meeting limits. All mixes exceeded 9 kN stability, with 50% RA showing the highest at 15.7 kN. Flow values (2.2–3.4 mm) were within the 2–4 mm range. ITS results showed maximum tensile strength ratio (TSR) of 96% at 50% RA. Stripping and drain down tests confirmed RA's suitability. The findings indicate that RA can be used in DBM mixes while meeting MoRTH standards.

Keywords: Recycled Aggregates, Dense Bituminous Macadam, Marshall Properties, Stripping, Drain Down, ITS

1. Introduction

The depletion of natural resources in recent years has necessitated the adoption of sustainable construction practices, emphasizing environmental conservation and resource efficiency. The construction industry is increasingly shifting toward eco-friendly alternatives, and use of recycled aggregates (RA) has emerged as one of the most effective solutions to mitigate environmental pollution. Among these alternatives, the application of RA in bituminous concrete presents a practical and sustainable option, particularly when implemented using established design approaches such as the Marshall Mix Design technique. This study explores the feasibility of incorporating RA, either partially or fully, as a substitute for natural aggregates (NA) in Dense Bituminous Macadam (DBM) and evaluates the corresponding effects on mixture performance. Bituminous concrete is broadly used in the construction of flexible pavements due to its cost-effectiveness, durability, and minimal maintenance requirements [1]. However, its conventional production relies heavily on NA, which leads to the over-exploitation of natural resources and contributes to environmental degradation [2, 3]. India, being the most populous country, is witnessing rapid urbanization accompanied by large-scale construction, demolition, and renovation activities [4, 5]. As a result, the nation generates approximately 150 million tonnes of C&D waste annually. Despite this volume, the country currently operates only 34 authorized recycling facilities, collectively handling less than 1% of the total C&D waste produced. Consequently, the majority of this waste is disposed of unscientifically—either dumped in open fields, used as unprocessed landfill material, or discarded in unauthorized locations—posing significant threats to soil and groundwater quality, particularly during monsoon seasons [6, 7].

To address these challenges, the incorporation of RA into hot-mix asphalt (HMA) emerges as a viable solution [8-10]. Previous research suggests that substituting RA for NA can significantly reduce the consumption of virgin aggregates while maintaining the mechanical integrity of the mix, provided that appropriate mix design adaptations are made. This approach not only diverts C&D waste from landfills but also aligns with global sustainability goals [11, 12]. Nevertheless, due to the inherent variability and heterogeneity of RA, stringent material characterization and proper mix optimization are essential to ensure consistency and reliability in performance [5, 13]. Enhancing the understanding and development of such advanced techniques for RA utilization in bituminous concrete is critical for promoting long-term durability and sustainability of pavement structures.

The key objective of the present study is to evaluate the viability of partially or fully replacing NA with

RA in DBM and to analyze the performance outcomes using Marshall stability parameters, Indirect Tensile Strength (ITS), stripping, and drain down tests. The investigation aims to formulate a comprehensive approach for the effective utilization of RA in DBM, thereby addressing the safe disposal of C&D waste through its incorporation into road construction. Moreover, the findings are expected to donate valuable results into the performance capacities and limitations of RA-based mixes.

The use of reclaimed or recycled aggregates in bituminous concrete mixtures is being extensively researched to assess both economic and environmental benefits. Several studies have demonstrated the successful inclusion of RA in bituminous mixtures without significant compromises in performance when proper design protocols are followed [14]. Various waste materials such as C&D debris, foundry sand, Reclaimed Asphalt Pavement (RAP), and industrial slag have been investigated as partial replacements for Natural aggregates [15, 16]. These studies generally conclude that recycled materials can be effectively utilized up to certain limits without deteriorating mix performance, provided essential performance tests such as ITS, stripping, and drain down are considered in the mix design [17-19]. Recent research has also evaluated the utilization of Recycled Concrete Aggregates (RCA) within Hot Mix Asphalt to enhance pavement sustainability. When treated properly, RCA has shown promising results in improving or maintaining mix durability and stability [20, 21]. However, variability in RCA properties and potential moisture susceptibility continue to pose challenges that require careful evaluation and design modifications [22-24]. Minor changes in mix proportions and Marshall Parameters have been found to significantly influence the performance of recycled mixes. Many researchers have focused on evaluating the effectiveness of recycled aggregates in DBM and Bituminous Concrete (BC) layers. These investigations suggest that with appropriate aggregate gradation and blending ratios, RA-based mixtures can achieve performance comparable to conventional mixes [25, 26]. One particular study examined the inclusion of high percentages of RAP into BC mixes and concluded that RAP could be used up to 50% without adversely affecting mechanical behavior, presenting a strong case for its environmental advantages [27, 28]. Life-cycle analysis studies have also highlighted significant energy savings and reductions in carbon footprint associated with RA use in asphalt production. Moreover, investigations have shown that incorporating RA into HMA not only enhances durability but also improves damage resistance by moisture, an important factor in extending pavement lifespan [29, 30]. Innovative processing techniques and new material technologies further promise improved performance for RA-based HMA mixes, indicating a bright future for sustainable pavement systems. The studies on percentage replacement of NA with various waste materials are summarized in Table 1.

In continuation of these findings, the present study investigates RA substitution at 25%, 50%, 75%, and 100% in DBM, as per MoRTH and MS-2 guidelines. Initial stripping tests were conducted to ensure the suitability of RA, followed by a detailed performance evaluation using standard laboratory methods.

2. Materials and Methods

This section of article will explain the experimentation procedure followed in step by step as shown in figure 1. Materials were collected from known nearby sources. Laboratory tests were performed on bitumen (VG-30) as per IS 1202, 1203, 1205, 1206, 1208, 1209. The basic tests on natural and recycled aggregates were conducted in laboratory to study their physical properties as per IS 2386. In addition to that, the stripping test was performed on aggregates as per AASHTO T283. The aggregate gradation was done by Job Mix Formula method and satisfying the MoRTH DBM Grade-II specifications.

Table 1. Summary of percentage replacement of waste materials in mix

Source	Dosage of Natural Aggregate Replacement (%)	Outcomes
[31]	5, 10, 15, 20, 25, 30	Maximum 25% RAP in mix satisfied the bituminous concrete requirements.
[32]	10, 20, 30	RCA of 30% in mix showed best results.
[33]	10, 20, 30, 40, 50	30% RCA replacement makes the road construction economical and sustainable.
[34]	5, 10, 20, 30	Good Marshall performance, high stiffness, and moderate resistance to water percolation.
[35]	10, 15, 20	15% replacement yielded optimal mix properties.

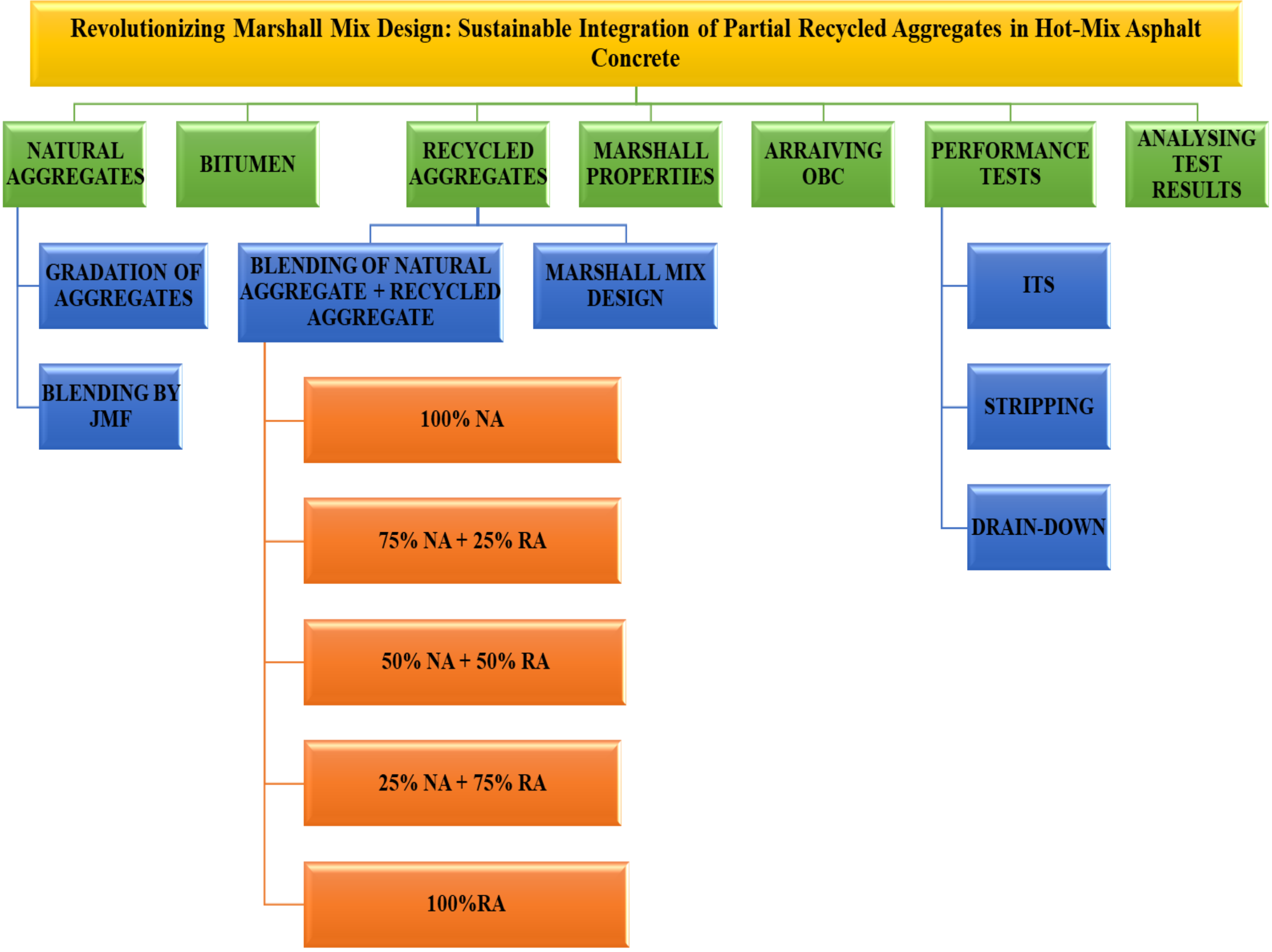

Figure 1. Flowchart showing methodology

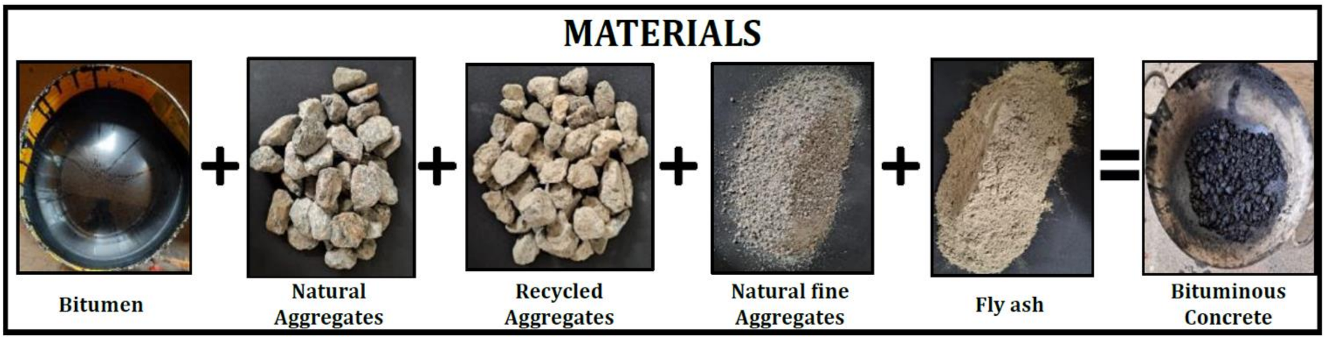

Figure 2. Materials used in laboratory study

Replacement of natural aggregates by recycled aggregates of 25%, 50%, 75% and 100% (MD 1 to 5) was done. For instance, 75%NA + 25%RA represents the mixture containing 75% Natural aggregates & 25% recycled aggregates. The Marshall specimens were casted as reference to blending proportionate to find out the Marshall Properties and TSR. Then the drain down test conducted on prepared mix. The below flowchart outlines the process involved in preparing the bituminous concrete mix by incorporating with RA and performance evaluation by Marshall test properties, Drain down test and Indirect Tensile Strength test for all mixes.

The materials used in this present study are natural aggregates, recycled aggregates, bitumen of VG-30 & fly ash. The final product of these materials formed the bituminous concrete mixture as shown in figure 2. It is very much essential to know the physical properties of materials to prepare the blending proportions. Hence, the laboratory tests conducted on the bituminous concrete ingredients and their physical properties were explained as follows.

2.1 Natural aggregates

Natural aggregates such as crushed stone, gravels and sand are the main ingredients of conventional bituminous pavement concrete. The physical properties like shape, gradation and mineral composition of aggregates will affect the performance and properties of bituminous mix. Proper gradation provides good interlocking and distribution of binder which will increase the resistance to fatigue and rutting. Greater frictional properties and stability will be possible with the roughly textured and angular aggregates. Durability of mix depends on abrasion resistance and Hardness. Adhesion with bitumen binder is affected by Mineral composition of aggregates. Having the knowledge on these factors is essential for designing and construction of the proper bituminous concrete pavement. The natural aggregate materials were collected from local quarry and physical tests were performed confirming Indian Standard codes. The obtained test results are tabulated in table 2.

2.2 Recycled Aggregates

Recycled aggregates are the derivatives of construction and demolition (C & D) waste. These materials are the best solution for avoiding the environmental burden caused by disposal of waste and depletion of natural resource. These recycled aggregates will be obtained by the processing of C & D wastes. Recycled aggregates mechanical and physical properties have made them suitable for different construction usage. The utilization of recycled aggregates in construction will reduce the depletion of natural resources and congestion in landfill. Understanding the characteristics and performance of recycled aggregates is essential for promoting their widespread adoption in sustainable construction practices. These materials were borrowed from a C & D waste separation and processing plant. The tests were performed on recycled aggregate in laboratory and physical properties were tabulated and compared with natural aggregates in the table 2.

All the results obtained for the natural aggregates and recycled aggregates are within the MoRTH specifications and also as per the IS codes. But, the obtained water absorption value of recycled aggregates is greater than 2%, which is greater than the MoRTH requirement. This is due to the presence of pores, dust and traces of cement mortar on the surface of recycled aggregates, which will absorb the water content greater than the natural aggregates.

2.3. Binder – Bitumen VG-30

Bitumen VG-30, a widely used paving grade bitumen, holds paramount significance in asphalt pavement construction due to its versatile properties and applications. This penetration-grade bitumen, characterized by its intermediate viscosity and penetration value, serves as a crucial binder in the formulation of asphalt mixes. Its optimal softening point, ductility, and adhesion properties contribute to the performance and durability of asphalt pavements under diverse climatic and traffic conditions. Bitumen was purchased from a nearby dealer.

Table 2. Comparative Test Results of Natural and Recycled Aggregates

Sl. No.	Test	Physical properties		DBM	Test as per IS Codes:
		Natural Aggregates	Recycled aggregate	MORTH Specification	
1.	Combined Flakiness & elongation index	28.51%	24.16%	≤30%	IS:2386 Part-I [36]
2.	Crushing Strength test	25.72%	22.70%	≤30%	IS:2386 Part -IV [37]
3.	Aggregate impact test	22.40%	20.68%	≤ 24%	IS:2386 Part –IV [37]
4.	Abrasion test	27.20%	24.8%	≤ 30%	IS:2386 Part IV [37, 38]
5.	Sp. gravity 4.75mm down 12.5mm down 20mm down 40mm down	2.65 2.62 2.65 2.71	2.80 2.85 2.90 2.90	Satisfactory	IS:2386 Part- III [38]
6.	Absorption Water 40mm down 20mm down	0.6% 0.9%	2.4% 2.8%	≤ 2%	IS:2386 Part-III [38]

Table 3. Characteristics of Bitumen VG-30

Sl. No.	Tests Performed	IS Codes Referred	Test Results	MORTH 500 Requirements
1	Penetration Test	IS-1203 [39]	68 mm	60-70 mm
2	Softening Point Test	IS-1205 [39]	50°C	> 47°C
3	Ductility Test	IS-1208 [39]	100 cm	> 75 cm
4	Flash Point Test	IS-1209 [39]	250°C	> 220°C
5	Specific Gravity Test	IS-1202 [39]	1.01	0.99-1.03

Table 4. Test physical Results of Class F Fly Ash

Sl. No.	Tests Performed	IS Codes Referred	Test Results	Specifications
1	Specific Gravity	IS 1727:1967 [40]	2.2	2.1-2.5
2	Moisture Content	IS 1727:1967 [40]	0.2%	< 2%

Physical tests on bitumen were carried out as per the Indian standard code's specifications and requirements of bitumen confirming MORTH Section 500. The obtained test results were listed in table 3.

2.4. Filler – Fly ash

Class F fly ash is a by-product which is obtained by power plants coal combustion, is utilized as a filler material in this study. Known for its pozzolanic properties, Class F fly ash enhances the performance and durability of asphalt mixtures by improving binder-aggregate adhesion and reducing voids. Since fly ash particles were very fine in nature leads to achieving the better compaction, workability and density of pavements. The physical tests were performed on fly ash and results were listed in table 4.

2.5 Stripping Test on Recycled and Natural Aggregates

The stripping test on natural and recycled aggregates was conducted in AASHTO T283 accordance to evaluate the susceptibility of moisture in the aggregates as shown in the figure 3. This test measures the resistance of the aggregate and bitumen bond to stripping, which occurs when water penetrates the asphalt mix and reduces the adhesion between the aggregate and bitumen [18, 19, 41]. By comparing the stripping values of natural and recycled aggregates, the test evaluates durability and longevity of asphalt pavement in the presence of moisture. The obtained test results were tabulated in the table 5.

The minimum retained coating must be 95% according to MoRTH specifications. The results obtained for both type of aggregates satisfies MoRTH specifications.

2.6. Mix Design Parameters

2.6.1. Aggregate gradation and blending proportion using Job Mix Formula

Aggregate gradation and blending proportions were important processes in bituminous concrete mix design with maintaining the performance characteristics and durability. To identify the ideal mixing combination of aggregate with different sizes, Job Mix Formula (JMF) is applied. The blending of Aggregates involves the combination of different aggregate sizes in precise proportions. The gradation combinations are explained in table 6 and the distribution of particle size is mentioned in figure 4 which satisfies MORTH specifications [42]. The aggregate proportions of blending in the mix are listed in table 7.

2.6.2. Preparation of Marshall Specimens

For every mix design 15 specimens were prepared using 1200 grams of aggregates for each specimen, based on the aggregate blending. Then, tested for their Marshall properties and ITS as shown in figure 5. The 1200 grams of aggregate materials were heated up to a temperature between 150°C to 175°C, while the binder heated to temperature between 150°C to 165°C. The mixture was then transferred to a mold and 75 blows applied for compaction on each side at a temperature between 140°C and 150°C. For subsequent trials, the bitumen content was adjusted with ± 0.5%, and the same procedure was followed repeatedly. 3 specimens were prepared for individual bitumen percentage variation to evaluate stability, density, air voids, VMA, flow and VFB [43].

3. Results and Discussion

The table 8 shows the properties of Marshall Mix for natural aggregates (NA) and with different percentages of reclaimed or recycled aggregates (RA). The Marshall molds were prepared as per the mix design calculations, then tested to achieve optimum bitumen content (OBC), air voids, bulk density, stability, flow, voids filled with bitumen (VFB) & voids in mineral aggregates (VMA). The obtained test results are checked whether they meet the MoRTH specifications for evaluation. This complete process of analysis will help to understand the suitability of integrating recycled aggregates in bituminous concrete mixes.

Table 5. Stripping test results

Type of Aggregates	Retained Coating (%)	Stripping value (%)
Natural	98%	2%
Recycled	96%	4%

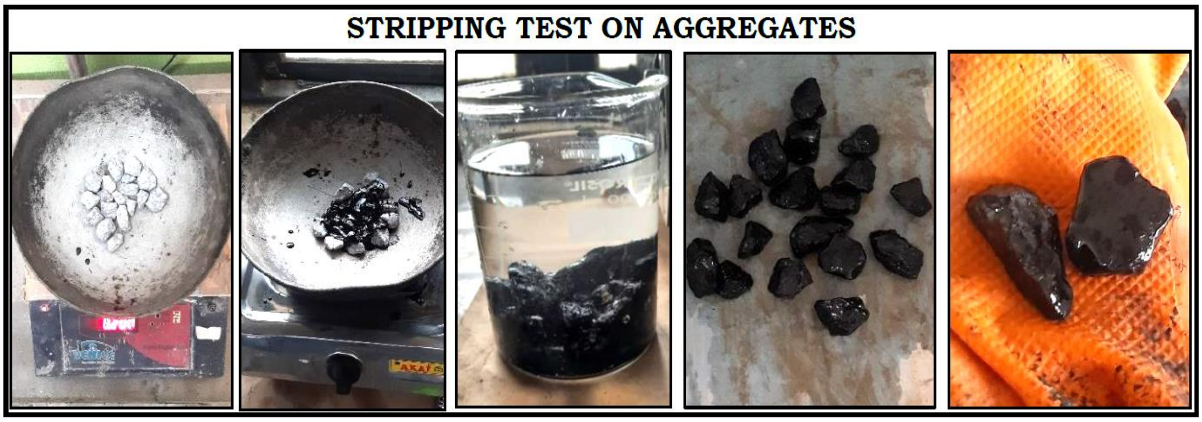

Figure 3. Stripping test on aggregates

Table 6. Gradation and blending of aggregates by Job Mix Formula

Sieve Size (mm)	Percentage of Passing					Blending	MORTH Specified Limits		
						24%			
	40-20 (mm)					18%			
		20-12.5 (mm)				20%			
			12.5-4.75 (mm)			36%	Lower Limit	Upper Limit	Mid Value
				4.75 (mm) down	Filler	2%			
37.50	100	100	100	100	100	100	100	100	100
26.50	94.45	100.00	100.00	100.00	100.00	98.67	90	100	95
19.00	68.56	74.23	100.00	100.00	100.00	87.82	71	95	83
13.20	13.34	28.45	100.00	100.00	100.00	66.32	56	80	68
4.75			38.48	98.00	100.00	44.98	38	54	46
2.36			18.42	86.37	100.00	36.78	28	42	35
0.30				34.56	100.00	14.44	7	21	14
0.075				8.54	100.00	5.07	4	8	6

Table 7. Blending proportions of aggregates

Aggregate Size	Blending proportion	Individual weight of Aggregates							
		MD (1)	MD (2)		MD (3)		MD (4)		MD (5)
		NA	NA	RA	NA	RA	NA	RA	RA
		100%	75%	25%	50%	50%	25%	75%	100%
40mm	24%	288	216	72	144	144	72	216	288
20mm	18%	216	162	54	108	108	54	162	216
12.5mm	20%	240	180	60	120	120	60	180	240
4.75mm	36%	432	324	108	216	216	108	324	432
Filler	2%	24	-	24	-	24	-	24	24
Total Weight (gms)	100%	1200	882	318	588	612	294	906	1200

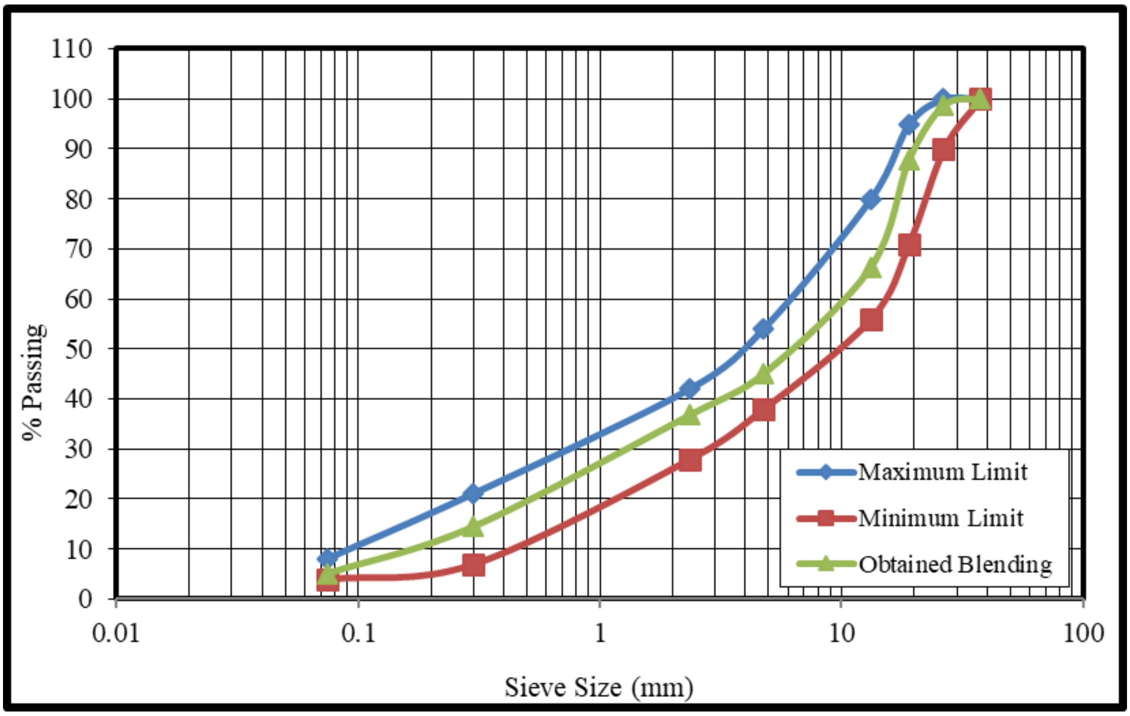

Figure 4. Gradation curve

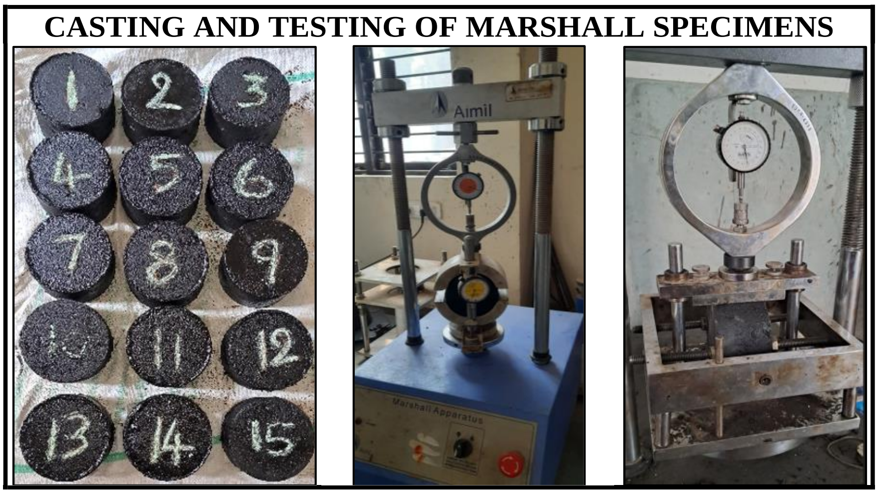

Figure 5. Preparation and testing of Marshall Specimens

Table 8. Properties of Marshall Mix for natural and different percentage of recycled aggregate

DBM	MD (1)	MD (2)		MD (3)		MD (4)		MD (5)	MoRTH Specifications
Type of Aggregate	NA	NA	RA	NA	RA	NA	RA	RA	
NA + RA	100%	75%	25%	50%	50%	25%	75%	100%	
OBC (%)	4.6	4.5		4.5		4.63		4.72	Minimum 4.5%
Bulk Density (g/cc)	2.38	2.41		2.42		2.43		2.45	-
Air Voids (%)	4.64	4.42		3.89		3.80		3.6	3 to 5 %
Voids In Mineral Aggregates (%)	15.08	16.1		15.7		15.62		14.33	Minimum 13%
Voids Filled with Bitumen (%)	69.24	72.6		74.56		74.91		75.00	65 to 75 %
Stability (kN)	11.89	13.5		15.7		14.54		13.78	Minimum 9kN
Flow (mm)	2.2	2.3		2.6		3.1		3.4	2 to 4 mm

The maximum OBC of 4.72% was obtained at MD-5 with 100% of reclaimed or recycled aggregates, due to the porous nature of aggregates surface causing higher absorption of bitumen. Despite this, the OBC values for all mixes fell within the range prescribed by MoRTH specifications, which is 3% to 6%. It is found that, the minimum required OBC for Dense Bituminous Macadam (DBM) mix is 4.5%.

3.1 Analysis and comparison of Marshall Properties between the mix with natural aggregates and different percentage of reclaimed aggregates

3.1.1 Bulk density

`An increase in bulk density is observed with the higher percentage of reclaimed aggregates. This trend can be attributed to the denser packing of aggregates and the improved interlocking mechanism provided by the reclaimed materials. As proportion of recycled aggregates increases, the void spaces within the mix decrease, leading to a more compact and stable structure. Consequently, this results in enhanced load-bearing capacity and overall durability of the asphalt mixture.

3.1.2 Air voids

The obtained air voids of all the designed mixes are ranging between 3% to 5% which will meet the requirements of MoRTH Specifications Section 500. It is observed that; the air voids decrease with increase in percentage of reclaimed or recycled aggregates in bituminous concrete mix. The reason behind this behavior may be due to high OBC and increased bonding caused by reclaimed or aggregates. So, that increased interlocking act will Reduces the voids and forming bituminous mix as denser as well as durable.

3.1.3 Voids in Mineral Aggregates (VMA)

All mix designs achieved the Voids in Mineral Aggregates (VMA) greater than 13% which will meet the requirement as per MoRTH Specifications mentioned in Section 500. It is observed that, there is a decrease in VMA as the percentage of reclaimed or recycled aggregates increases, but still satisfying the requirements.

3.1.4 Voids Filled with Bitumen (VFB)

It must be in between 65% to 75% as per specifications of MoRTH section 500. The above mix designs are exibuiting the results in this range only. The VFB is incresed with increase in the percentage of reclaimed or recycled aggregates. It will clearly indicates the improvement in coating of bitumen and reduction in voids. Hence, this analysis concluds the improvement in ability of bitumen concrete mix to strogly hold the binder which will leads to durability and better compaction.

3.1.5 Stability

The minimum stability value of mix must be 9kN as mentioned in the MoRTH Section 500. All bituminous concrete mixes of this study achieved stability values well above this requirement. The highest stability value of 15.7 kN was achieved with MD-3 (50% natural aggregates and 50% reclaimed aggregates). This indicates that incorporating reclaimed aggregates up to 50% enhances the stability of the mix, providing a more strong and durable pavement structure. However, the stability values decrease slightly beyond 50% reclaimed aggregates, possibly due to the increased variability in the reclaimed aggregates, which can affect the mix's homogeneity and the interlocking of particles.

3.1.6. Flow

The flow value must be between 2 to 4 mm as mentioned in MoRTH Section 500. The mixes tested in current study have shown flow values ranges between the specifications of MoRTH. By the results it is confirmed that, the interpretation of reclaimed or recyled aggregate in the mixes will not negatively affect the charectoristics of flow. The Recycled aggregates have varying particle shapes or surface characteristics when compared with natural aggregates which will affect the ability of aggregates to properly interlock and binding of bitumen. Otherthan these behaviours, all mixes shown the flow values between permissible range and also by providing the better performance pavement and adequate workability.

3.2. Indirect Tensile Strength (ITS)

The Indirect Tensile Strength (ITS) test is adopted to measure the resilience and tensile strength of bituminous concrete mix. As per the specifications mentioned in MoRTH and ASTM D6931, the ITS test conducted by casting the cylindrical specimens and applying compressive loads diametrically. Then load at the failure of specimen will be noted down [44].

The Indirect Tensile Strength (ITS) value will be calculated by the formula

$S=(2000P/\pi tD)$ kN/m^2.

The obtained test results and ITSR values were tabulated in the table 9.

Where, S= Tensile strength (kN/m^2)

P = Maximum Load (kN)

t = Thickness of Specimens (m)

D = Dia. of specimen (m)

The Indirect Tensile Strength Ratio (ITSR) results for the five mix designs (MD-1 to MD-5) illustrate the impact of incorporating recycled aggregates on the resilience of asphalt mixes. MD-1, composed entirely of natural aggregates, exhibits a ITSR of 84%, indicating good tensile strength retention under conditioned and unconditioned states. As the percentage of reclaimed aggregates increases in MD-2 to MD-5 (25%, 50%, 75%, and 100% respectively), ITSR values show varying trends, with MD-3 achieving the highest ITSR of 96% at 50% reclaimed aggregates. This suggests that moderate levels of reclaimed aggregates enhance tensile strength and durability. However, mixes with higher reclaimed aggregate content, such as MD-4 and MD-5, exhibit slightly lower ITSR values (93% and 86% respectively), indicating some compromise in tensile strength under severe conditions. Overall, while reclaimed aggregates offer sustainability benefits, optimizing their proportion in mix designs is crucial to balancing performance and durability in asphalt pavements.

3.3. Drain down

The prepared Marshall mixes subjected to drain down test procedure confining to ASTM D6390 to find out the resistance for drainage of binder in bituminous mixtures [45]. This test is very much essential to calculate quantity of bitumen that will drains out of the aggregate mix when tested at higher temperatures. The stages involved while performing the test were shown in the figure 6.

This test helps to understand the durability and stability of mixes. Also, gives an idea regarding the suitable percentage of bitumen to a selected mix which plays an important role in maintaining structural uprightness during storage, transporting and laying [46]. The obtained test results of various Marshall Mixes are shown in the table 10.

Table 9. Indirect Tensile Strength Ratio (ITSR) test results

Mix	Conditioned S2 (kN/m^2)	Unconditioned S1 (kN/m^2)	ITSR=(S2/S1) *100 (%)
MD-1	1.35	1.60	84
MD-2	1.19	1.35	88
MD-3	1.40	1.45	96
MD-4	1.46	1.57	93
MD-5	1.20	1.38	86

Figure 6. Drain down test on Marshall Mix

Table 10. Drain Down test results

Mix Name	Wt. of sample retained on plate	Wt. of sample taken	Drain down in %
MD-1	22	1258	1.75
MD-2	18	1262	1.43
MD-3	9	1269	0.71
MD-4	6	1271	0.47
MD-5	2	1279	0.16

The results of drain down test on different Marshall mix designs shown a capacity of aggregates to hold the bitumen. The maximum value of drain down is 1.75% for MD-1, which is the mix prepared with 100% of natural aggregates showing the notable percentage of bitumen drain from mix. It indicates that, the drain down values decreased with increase in recycled aggregates percentages. The gradual decreased drain down value observed from mix MD-2, MD-3, MD-4 and. Finally, MD-5 consisting entirely of recycled aggregates, has the lowest drain down value at 0.16%, demonstrating the best bitumen retention among all mixes. These findings suggest that higher percentages of recycled aggregates enhance the bitumen retention capacity of the asphalt mix.

4. Conclusion

The results of this study validate that, all the bituminous concrete mixes were able to achieve the minimum Optimum Binder Content (OBC) requirement of 4.5%, with the highest OBC of 4.72% being recorded for the 100% Recycled Aggregate (RA) mix. A rise in RA content was accompanied by an increase in bulk density, which indicates a denser mix, with the highest recorded at 2.45 g/cc for the 100% RA mix. In addition, air voids also showed a decreasing trend with increasing RA incorporation, but were within the acceptable limit of 3% to 5%. Voids in Mineral Aggregate (VMA) always exceeded the minimum requirement of 13% for all mixes, providing sufficient binder film thickness and mix durability. In a similar vein, the Voids Filled with Bitumen (VFB) values were within the specified range of 65% to 75%, with the maximum value of 75% from the 100% RA mix. Stability tests revealed that the mixes exceeded the specified 9 kN, and the highest stability of 15.7 kN was attained by the 50% RA mix, which implies improved load-carrying capacity. The flow values for all the mixes were within the acceptable range of 2 to 4 mm, providing resistance to deformation in loading for the mix. Furthermore, the analysis of Tensile Strength Ratio (TSR) pointed out that the highest resistance to moisture was seen for the 50% RA mix with a TSR of 96%. These findings in total prove the viability of using recycled aggregates in bituminous concrete without sacrificing compliance with performance specifications, hence enabling sustainable construction of pavements.

By analysing all the mix designs properties, it proves that the mix number MD-3 (50%NA + 50%RA) is the optimum mix. The use of RA is suitable up to 50% and further more increase in RA% leads to increase in OBC and decrease in stability. The use of recycled aggregates 50% in the bituminous concrete mix instead of natural aggregates will reduce the negative environmental impact and reduce the risk of natural resource depletion.

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Authors Contribution Statement

J. Prakash: Conceptualization, methodology, investigation, writing–original draft, review and editing, data curation, visualization. B.H. Manjunath: Methodology, Conceptualization, Writing–Review and Editing, Supervision, Resources. S.N. Neeraj: Methodology, Conceptualization, Writing–Review and Editing, Supervision, Resources. H. Sagar: Writing - Review & Editing, supervision, Resources. D.Y. Chaya: Writing - Review & Editing, supervision, Resources. All the authors read and approved the final version of the manuscript.

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Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Scope for further work

The further detailed investigation can be done to evaluate the rutting behaviour and crack study of recycled aggregate bituminous concrete mix for analysing the practical application in road construction.

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