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Performance and Economic Evaluation of RAP-Incorporated Asphalt Mixes for Local Road

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Fracture Resistance

ABSTRACT

Reclaimed Asphalt Pavement (RAP) offers a practical route to reduce material consumption and construction cost in asphalt paving, yet its adoption in Pakistan remains constrained by limited local performance–cost evidence. This study investigated the mechanical and economic feasibility of RAP-incorporated hot mix asphalt using locally sourced materials and market-based cost data. Mixtures containing 0%, 25%, 50%, and 75% RAP were designed using the Marshall method, and their performance was evaluated through volumetric analysis, Marshall stability, and semi-circular bending (SCB) peak load testing. Economic assessment was conducted using contractor quotations cross-checked with the Market Rate System (MRS-2024). The optimum binder content was 4.40%. Among all mixtures, the 25% RAP mixture delivered the best overall balance of structural response and cost efficiency, increasing Marshall stability from 9.40 kN to 14.28 kN, equivalent to a 51.9% improvement, while reducing estimated construction cost by 13.8% relative to the virgin mixture. Higher RAP contents showed lower SCB peak load, indicating that excessive aged binder increased mixture stiffness and brittleness, reduced effective blending with the virgin binder, and limited the mixture's ability to dissipate fracture energy. For the materials and testing conditions investigated, 25% RAP is identified as the most practical and sustainable replacement level for local road applications.

1. Introduction

In Pakistan, road transport is the dominant mode for both passenger and freight movement, which makes the sustainable development of pavement infrastructure particularly important [1]. The United States was among the earliest countries to adopt large-scale eco-efficient pavement practices involving recycled asphalt pavement (RAP), and annual RAP reuse has been reported to exceed the combined recycling volume of paper, glass, plastic, and aluminum in some years [2]. Therefore, the use of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) has emerged as an important sustainable practice because it reduces the demand for virgin materials while improving resource efficiency [3].

In general, the tendency towards more sustainable construction technologies of pavements has been increasing worldwide, where a great deal of work related to pavement design and the circular economy can be found [4,5]. In these cases, RAP recycling also offers the environmental and economic benefits [6,7]. This also results in an economical benefit, because the aggregates and the binder are less utilized, and therefore it is unnecessary to transport these materials to the site of the plant [8,9]. The reduction of raw materials has a direct impact in consumption of energy to get, move, and process these goods [10]. It also eliminates the need for non-renewable resources and a lot less landfill space and transportation for disposing of used materials from the paving process [8,9].

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As per international studies, the use of Reclaimed Asphalt Pavement (RAP) in asphalt mixtures could decrease construction costs as much as 34% while life-cycle costs have been reported to decrease up to 14% [11]. This is primarily because there will be less of the need for virgin aggregates and binders [12,13].

Several of these studies focus on the use of RAP-based mixes as well as the percentage of replacement. For instance, Marshall stability was reported to increase using 15–30% RAP in some of these studies and the asphaltic mixture became stiffer at higher RAP contents when using more than 40% RAP [15,16,17,18]. Along this line, one study found that blends with 25% RAP performed acceptably well

in terms of durability and fracture-controlled mix design, but mixtures with 50% or more RAP required the use of modified binders or rejuvenators in order to attain acceptable cracking performance [15,19,20]. This indicates that the RAP percentage has a critical influence on performance characteristics of the blend.

Previous life-cycle studies have reported that RAP can reduce material demand, construction cost, energy use, and greenhouse-gas emissions, although the magnitude of benefit depends on RAP content, haul distance, binder demand, and recycling process [21,22]. For a developing country like Pakistan, which has a road network of more than 100,000 kilometers, RAP could be an appealing alternative for the environmental impact that the disposal of materials like asphalt presents [5,23]. Current studies in 2021 to 2024 conclude that "by choosing suitable binder grades and using of rejuvenators the performance of Hot Mix Asphalt (HMA) mixtures with moderate to high RAP contents can specific from standard mixtures or even exceed it" [24,25].

Life-cycle cost analyses show that the use of RAP has been found to consistently give lower costs, with reports of 6–16% savings for asphalt mixes with RAP contents at 30–70%, with also some energy and CO_2 savings [26,27]. More general comparative studies have drawn cost savings between ~5% and 30% or more, which are influenced by binder prices, transport distances, and recycling technologies [28]. On top of that, the environmental and economic benefits of warm-mix technologies are enhanced when combined with higher RAP contents, further supporting the potential for Pakistan to realize similar benefits with the adoption of optimized RAP initiatives [26,27,28].

While international studies have also documented between 9% and 30% cost savings in the actual construction performed as well as 14% in the overall life-cycle cost of infrastructure when RAP is used, it is evident that the savings in material collection and hauling are substantial on a global basis [2,12,21]. Nonetheless, a gap in literature regarding the economic viability of RAP in Pakistan in local market conditions is observed [23,30]. Having identified this gap, it is clear that a regional pricing-structure-specific cost analysis is necessary, as the economic feasibility of deploying sustainable materials and technologies plays a key role in their uptake within resource-poor contexts [31].

Accordingly, this study aims to evaluate both the mechanical performance and the cost efficiency of RAP-incorporated asphalt mixtures using locally relevant material sources and Pakistani market-based cost data.

2. Materials and Methods

An experimental and economic evaluation program was designed to assess the suitability of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) for road construction in Pakistan.

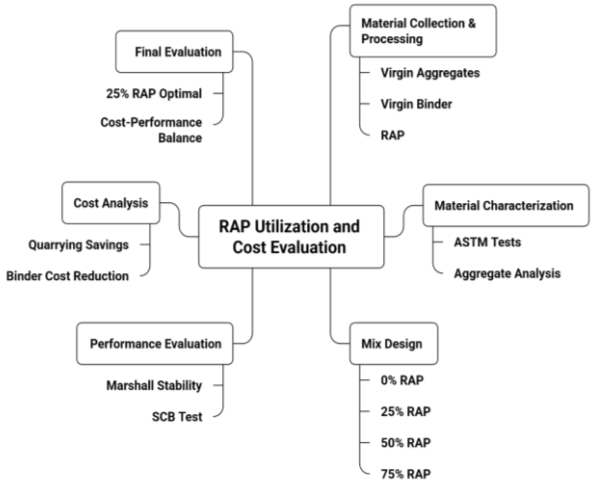

Fig.1. Framework for Proposed Methodology

2.1 Materials, Characterization, and Mix Design

Virgin aggregates were obtained from the Margalla quarry source, and 60/70 penetration grade bitumen from Attock Refinery was used as the virgin binder. Reclaimed asphalt pavement (RAP) was collected from milled pavement material obtained from Khanpur Road. To prepare RAP for mixture design, the reclaimed material was first air-dried, manually cleaned to remove extraneous debris, and then crushed and sieved to obtain a usable aggregate fraction. The RAP binder content was determined through extraction, and the recovered material was used to account for the contribution of aged binder in RAP-incorporated mixtures. Virgin aggregates and RAP aggregates were characterized using relevant ASTM procedures for crushing value, impact value, flakiness, elongation, water absorption, specific gravity, and abrasion resistance. The virgin binder was characterized through penetration, softening point,

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ductility, flash and fire point, and specific gravity tests.

Four hot mix asphalt (HMA) mixtures were prepared: a virgin control mixture and RAP-incorporated mixtures containing 25%, 50%, and 75% RAP. Marshall mix design was carried out in accordance with ASTM D6927 to determine the optimum binder content (OBC) using Marshall stability together with volumetric parameters, including air voids (Va), voids in mineral aggregate (VMA), and bulk density. Based on the combined volumetric and stability response, the optimum binder content was identified as 4.40%. As RAP content increased, the demand for virgin binder decreased because of the contribution of aged binder already present in the reclaimed material. The prepared Marshall specimens were subsequently used for mechanical and economic evaluation of the investigated mixtures. [3,5].

Virgin aggregates and RAP aggregates were characterized using relevant ASTM test methods for key physical and mechanical properties. The virgin binder was tested for penetration, softening point, ductility, flash and fire point, and specific gravity. RAP binder content was determined through extraction for mixture design purposes. The content of RAP binder was recovered through centrifuge extraction and analyzed along with virgin bitumen. Framework of research is shown in Fig.1.

Four Hot Mix Asphalt (HMA) mixtures decomposed as virgin (control sample), and 25%, 50% and 75% RAP HMA mixtures as shown in Fig. ***2***. The Marshall methodology (ASTM D6927) determined the OBC (Optimum Binder Content) using stability and volumetric properties. Higher RAP contents reduced the requirement for additional virgin binder because of the contribution of aged binder present in the reclaimed material, which has direct implications for material cost. Samples prepared by Marshall procedure and subsequently tested for stability and fracturing resistance are shown in **(**Fig. ***2*****)**. This therefore shows the structural feasibility, and cost saving potential of RAP in Pakistan [13,21,24].

2.2 Cost-Effectiveness and Performance Evaluation

The investigated mixtures were evaluated in terms of both mechanical response and construction cost. Marshall stability testing was performed in accordance with ASTM D6927 and was used as an indicator of mixture load-bearing resistance. Fracture-related behavior was assessed using the semi-circular bending (SCB) test in accordance with ASTM D8044. In the present study, semi-circular specimens were prepared from laboratory-compacted asphalt samples and tested under monotonic loading. The SCB specimens had a diameter of 150 mm, a thickness of 50 mm, and a notch depth of 15 mm. Testing was carried out at 25°C under a loading rate of 50 mm/min, and the maximum recorded load was reported as SCB peak load in kilo-Newtons (kN). These test conditions were selected to compare the fracture-related response of mixtures containing different RAP contents under a consistent loading configuration. The economic assessment was based on contractor quotations obtained from active pavement works in Khyber Pakhtunkhwa and cross-checked against the Market Rate System (MRS-2024). Cost comparison was performed in **Pakistani Rupees (PKR)** for the virgin mixture and the 25% RAP mixture by separating major cost components, including binder, aggregates and transport, plant and machinery, and labor. The reduction in total cost for RAP-incorporated mixtures was primarily associated with lower demand for virgin aggregates and virgin binder, whereas plant, machinery, and labor costs remained largely unchanged between the compared cases [25,27,32].

Fig. 2. Marshall specimens prepared with 25%, 50%, and 75% RAP

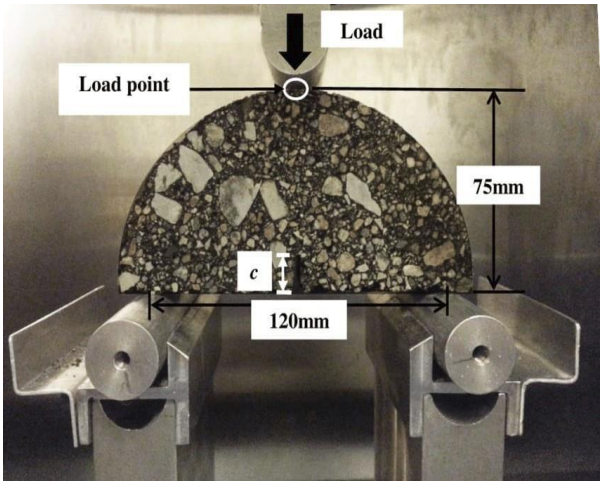

Fig. 3. Schematic of the semi-circular bending (SCB) test setup used to determine SCB peak load

Because the present study was designed primarily as a comparative laboratory investigation, the results are reported in terms of measured response values for each mixture condition. Formal statistical significance analysis based on replicate variability should be included in future work to strengthen inferential interpretation of the observed trends.

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Table 1

Virgin and RAP coarse aggregate test results

Test Performed	Virgin Coarse Aggre	RAP Coarse Aggre	ASTM Standard & Ranges	
Crushing Value Test	27%	29.19%	C151	< 30% for wearing course
Impact Value Test	7.99%	9.43%	C535	< 10% Very Strong
Flakiness	20.87%	22.49%	D4791	< 25
Elongation	12.79%	12.10%		
Specific Gravity of Aggregates				
Absorption %	0.08%	0.1%	C127	2.4-2.9
Bulk Specific Gravity (SSD)	2.2727 %	2.2095 %		
Bulk Specific Gravity	2.4545 %	2.4338 %		
Apparent Specific Gravity	2.7777 %	2.8492 %		
Abrasion Test	22.29%	26.07%	C131/ C131M	< 10% Low 10-20% Medium 20-30% High

3. Results and Discussion

3.1 Material Characterization: Aggregates and Binder

In order to make performance and cost results interpretable, both the aggregates and the binder underwent baseline tests. The mechanical properties of the virgin and RAP aggregates are presented in **Error! Reference source not found.**. Virgin aggregates complied with ASTM standards, crushing, impact and abrasion values were 27%, 7.99%, and 22.29% respectively all in typical values for a good structure; RAP aggregates, although slightly weaker, showed 29.19% crushing, 9.43% impact, and 26.07% abrasion, acceptable expected losses due to aging and milling degradation which are the price for a significant economic advantage [3,21].

The properties of the virgin 60/70 penetration grade binder and RAP binder are summarized in Table 2. Penetration (63,31), softening point (53.7°C, 64.8°C), and ductility (93 cm, 31 cm) are in accordance with ASTM standards, while the flash/fire points (190°C/240°C, 215°C/260°C) reflect the thermal stability. Because virgin binder accounts for more than 40% of the cost of asphalt, ascertaining the quality of this material is important prior to calculating the benefits of RAP replacement ratios [16],[33].

Table 2

Bitumen test results

Test performed	Virgin	RAP	ASTM Standard	ASTM Range
Specific Gravity Test	1.02	1.03	D-70	(0.97-1.02)
Softening Point Test	53.7°C	64.8°C	D36/D36M-09	(30-57) °C
Ductility Test	93cm	31cm	D-113	>53cm
Flash and Fire Test	190°C / 240°C	215°C/ 260°C	D-092	Min. 175°C / >200°C
Penetration Test	63	31	D-946	60/70 grade

Table 3.

Binder properties of RAP-incorporated mixtures

Property	0% RAP	25% RAP	50% RAP	75% RAP
Specific gravity	1.02	1.023	1.028	1.034
Softening point (°C)	53.7	56.0	58.8	62.0
Ductility (cm)	93	72	50	30
Flash point (°C)	190	198	206	216
Fire point (°C)	240	246	253	261
Penetration (dmm)	63	53	43	34

3.1.1 Estimated Properties of RAP-Derived Binder

Because the aged binder contained in RAP strongly affects mixture stiffness and cracking response, indicative binder-property trends were considered to support interpretation of the mechanical results. Based on the measured virgin binder properties and the observed stiffening behavior of RAP-incorporated mixtures, the effective blended binder was expected to

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show progressively lower penetration, lower ductility, and higher softening point with increasing RAP content. Approximate effective values for the investigated mixtures are summarized in Table 3. These values are engineering estimates intended to indicate the likely trend of the blended binder system and were not directly measured in the present study.

3.2 Mechanical Performance of RAP Mixtures

Mixture performance was assessed in terms of volumetric characteristics and mechanical response. As shown in Figure 4, air voids were 7.61%, 6.07%, 6.85%, and 8.05% at binder contents of 3.5%, 4.0%, 4.5%, and 5.0%, respectively. These values confirm that the minimum air-void content occurred at 4.0% binder content, while higher binder contents produced a subsequent increase in air voids. Over the same binder-content range, VMA increased from 13.35% to 15.11%, while bulk density varied only slightly between 2189 and 2201 kg/m³. Marshall stability increased from 9.40 kN at 3.5% binder content to a maximum of 14.28 kN at 4.0% binder content, after which it decreased to 12.82 kN at 4.5% and 9.10 kN at 5.0%. Based on the combined stability and volumetric response, the optimum binder content was selected as 4.40% for the present study. These results indicate that intermediate binder contents provided the most favorable balance between Marshall stability and volumetric suitability. The selected OBC of 4.40% reflects the combined stability, air-void, VMA, and density response rather than a single maximum-value criterion [12,21].

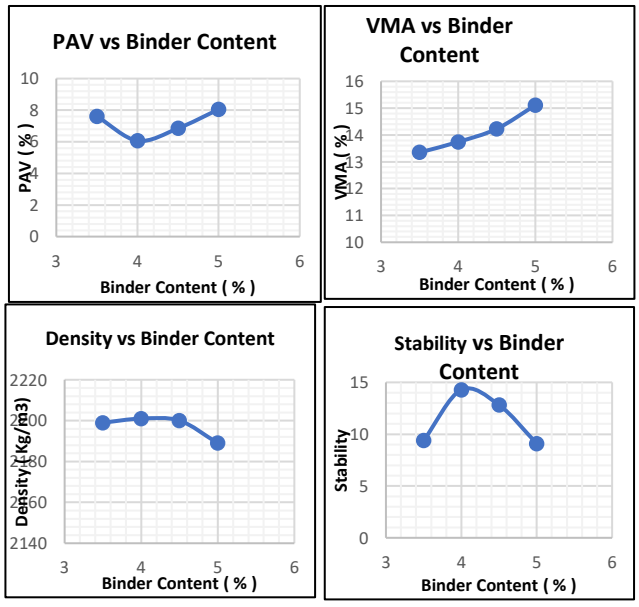

Fig 4. Volumetric and Stability parameters vs Binder content

Marshall stability and SCB peak-load results for RAP-incorporated mixtures are shown in Figures 5 and 6, respectively. Marshall stability represents load-bearing resistance under the Marshall test, whereas SCB peak load represents fracture-related resistance under monotonic semi-circular bending. Marshall stability increased from 9.40 kN for the virgin mixture to 14.28 kN at 25% RAP, corresponding to a 51.9% increase, and then decreased to 12.82 kN and 9.10 kN at 50% and 75% RAP, respectively. A comparable non-linear trend was observed in the SCB peak-load results: the SCB peak load increased from 5.41 kN for the virgin mixture to 8.12 kN at 25% RAP, before decreasing to 5.36 kN and 4.94 kN at 50% and 75%

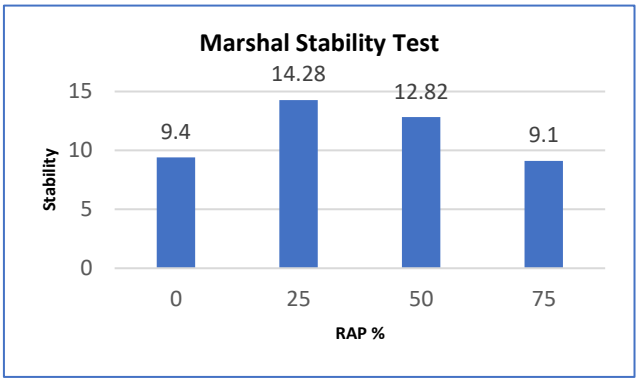

Figure 5:Marshall Stability vs RAP content

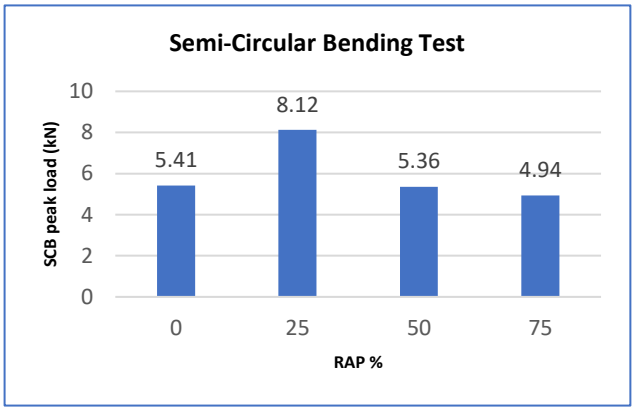

Fig. 6. SCB peak load (kN) versus RAP content

RAP, respectively. These findings indicate that moderate RAP incorporation improved both Marshall stability and SCB peak-load response under the present test conditions. At 25% RAP, the virgin binder likely provided sufficient blending and partial softening of the aged RAP binder, improving mixture stiffness without severely reducing fracture tolerance. At 50% and 75% RAP, the higher aged-binder fraction likely increased brittleness and reduced energy-dissipation capacity, causing the observed decrease in SCB peak load. The positive overall relationship between Marshall stability and SCB peak load suggests that moderate stiffness gain improved both load-bearing and fracture-related response. However, this relationship weakened at higher RAP contents because excessive aged binder increased brittleness; therefore, higher Marshall stiffness did not necessarily translate into improved cracking resistance. Within the scope of the present laboratory study, the 25% RAP mixture provided the most favorable balance between

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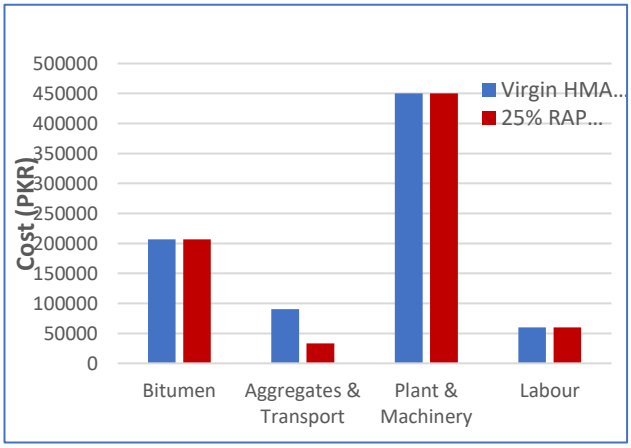
Marshall stability, SCB peak load, cracking-related response, and material efficiency. [3,35,36].

Within the scope of the present laboratory study, the 25% RAP mixture at an optimum binder content of 4.40% provided the most favourable balance between Marshall stability, SCB peak-load performance, fracture-related resistance, and cost reduction compared with the virgin control mixture [3].

3.3. Economic Evaluation of RAP-Modified Pavements

Specifically, one of the main objectives pursued within this research was not only to experiment and prove the technical feasibility of the use of RAP, but as well to address the economic aspect of RAP within the local market conditions. This was done by procuring direct cost estimates from Hamdard Enterprises, a contractor that is working directly on flexible pavement projects in Khyber Pakhtunkhwa, and cross-verifying these estimates by the Market Rate System (MRS-2024) provided by the government in the region. The estimated total cost of the virgin HMA case was PKR 870,000, whereas the corresponding 25% RAP case was estimated at PKR 750,200, as summarized in

& The decomposition in Fig. ***7*** indicates that the major cost savings were associated with material substitution, particularly reduced virgin aggregate



demand and related transport, whereas plant, machinery, and labor costs remained largely unchanged between the compared cases. These findings are in line with similar evidence from abroad, where well implemented RAP budgets generally result in direct cost savings of 9-30% and lifecycle savings of between 0-14%, and systematic reviews estimate savings between 5-68% based on the specific contents of the RAP and context of the program [1,2,3]. This convergence indicates that the 25% RAP mixture represents the most balanced option under the present local cost and laboratory-performance conditions, where the maximum Marshall stability and SCB peak load coincide with a 13.8% reduction in estimated construction cost.

Table 4. This represents an estimated cost reduction of 13.8%, primarily due to reduced demand for virgin materials, particularly binder and aggregates.

Fig. 7. Component-wise cost comparison of Virgin and 25% RAP HMA mixtures

The decomposition in Fig. ***7*** indicates that the major cost savings were associated with material substitution, particularly reduced virgin aggregate demand and related transport, whereas plant, machinery, and labor costs remained largely unchanged between the compared cases. These findings are in line with similar evidence from abroad, where well implemented RAP budgets generally result in direct cost savings of 9-30% and lifecycle savings of between 0-14%, and systematic reviews estimate savings between 5-68% based on the specific contents of the RAP and context of the program [1,2,3]. This convergence indicates that the 25% RAP mixture represents the most balanced option under the present local cost and laboratory-performance conditions, where the maximum Marshall stability and SCB peak load coincide with a 13.8% reduction in estimated construction cost.

Table 4

Direct Cost Breakdown: 25% RAP HMA (Contractor Quote + RAP processing, MRS basis)

Cost estimation components (MRS)	Virgin flexible pavement cost (MRS-2024)
Coarse Aggregates 9Cm*3 @ 3500/m*3	31500/-
Fine Aggregates 6M*3 @ C 3000/M*3	18000/-
Bitumen 1800kg @ R 110/kg	206736/-
Plant Mixing Cost	150000/-
Carry at site (Dampers)	150000/-
Paver machinery laying at site	150000/-
Site labor/ staff charges	60000/-
Transportation of coarse aggregates	25500/-
Transportation of fine aggregates	15300/-
Overall charges	870000/-

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Cost estimation components (MRS)	Reclaimed asphalt aggregates flexible pavement cost (MRS-2024)
RAP extraction (fuel)	15000/-
Electricity to run asphalt extractor (bill)	10000/-
Bitumen 1800kg @ R 110/kg	206736/-
Plant Mixing Cost	150000/-
Carry at site (Dampers)	150000/-
Paver machinery laying at site	150000/-
Site labor/ staff charges	60000/-
Further virgin coarser material required	8500/-
Total cost after 20% firm profit	750200/-

In order to improve the validity of such results, two extensions are suggested: (i) a sensitivity analysis of the binder price, haul distance, and RAP processing cost because variations in these values can change the estimated savings by a significant amount [2,4,13]; and (ii) a life-cycle cost analysis (LCCA) over a 15 to 25 year period to determine if potential savings remain in the medium term considering maintenance and overlay costs [21]. Future work should extend the cost analysis to higher RAP contents incorporating rejuvenators, particularly 50% RAP mixtures, because rejuvenators may improve binder blending and cracking resistance while retaining part of the material-cost advantage associated with RAP utilization [13,24].

3.4 Performance Cost Synergy of RAP Mixtures

The combined mechanical and economic results indicate that the 25% RAP mixture was the most favorable among the mixtures investigated in this study because it simultaneously achieved the highest Marshall stability, the highest SCB peak load, and a 13.8% reduction in estimated construction cost. In the Marshall and SCB tests shown in **Error! Reference source not found.** & **Error! Reference source not found.**, the 25% RAP mixture provided the highest Marshall stability and SCB peak load. This indicates that 25% RAP was the point at which stiffness enhancement from RAP improved structural response without causing the excessive brittleness observed at higher RAP contents. This overlap is significant because it shows that the 25% RAP mixture is the performance–cost 'sweet spot': the 13.8% cost reduction intersects with the maximum measured structural integrity, represented by the highest Marshall stability and SCB peak load. Previous RAP studies similarly indicate that moderate RAP contents, commonly around 20–30%, can provide a practical balance between mechanical performance, cost efficiency, and sustainability when binder blending remains adequate and cracking resistance is not compromised [3,36,37]. For Pakistani local-road applications, the 25% RAP mixture at 4.40% OBC therefore appears technically and economically preferable under the investigated conditions. However, higher RAP contents should not be adopted without binder-blending verification, rejuvenator evaluation, and cracking-resistance assessment.

Conclusion

This study evaluated the mechanical performance and direct construction-cost feasibility of RAP-incorporated hot mix asphalt mixtures under Pakistani local-material and market-rate conditions. Based on Marshall mix design, the optimum binder content was identified as 4.40%. Among the investigated mixtures, the 25% RAP mixture exhibited the most favorable overall response, providing the highest Marshall stability, the highest SCB peak load, and an estimated 13.8% reduction in direct construction cost compared with the virgin mixture. The cost benefit was mainly associated with reduced demand for virgin aggregates and related transport, whereas plant, machinery, and labor costs remained largely unchanged. The results indicate that moderate RAP incorporation can improve material efficiency while maintaining favorable laboratory performance. In contrast, 50% and 75% RAP reduced SCB peak load, indicating that excessive aged-binder content increased stiffness and brittleness, limited effective blending with the virgin binder, and reduced the mixture's capacity to dissipate fracture energy. Therefore, under the materials, mixture proportions, and test conditions investigated in this study, 25% RAP appears to be the most practical replacement level for local road applications. This study is limited by the absence of detailed long-term field validation and formal statistical significance testing based on replicate variability. Future work should therefore include repeated testing with statistical analysis, life-cycle cost assessment, and evaluation of rejuvenators in higher-RAP mixtures to determine whether higher recycling rates can be achieved without compromising cracking resistance.

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