A Scenario-based Case Study Approach to Pavement Rehabilitation using Life Cycle Analysis of Recycled Asphalt Materials

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ABSTRACT

This study evaluates the environmental and mechanical impacts of using Reclaimed Asphalt Pavement (RAP) and Crumb Rubber (CR) in asphalt rehabilitation. A Life Cycle Assessment (LCA) and laboratory testing, complemented by AASHTOWare analysis, were used to assess the mechanical properties and sustainability of various asphalt mixtures. The results show that a composition of 50% RAP and 30% CR offers the best balance of durability, cost efficiency, and environmental benefits. RAP improved rutting resistance, while CR enhanced elasticity and fatigue resistance at lower concentrations. Excessive RAP or CR caused brittleness and susceptibility to cracking. The LCA findings reveal reduced carbon emissions and material consumption, while the cost analysis showed significant savings in construction and maintenance. The AASHTOWare predictions confirmed improved service life and reduced pavement distress under varying traffic and climate conditions. This study demonstrates the potential of RAP and CR for sustainable, cost-effective pavement solutions while maintaining structural performance.

Keywords-life cycle assessment; life cycle cost assessment; pavement rehabilitation; recycled material; asphalt pavement; sustainability

I. INTRODUCTION

One of the major challenges in pavement engineering is meeting the ever-increasing demand for economic and physical resources needed for construction and maintenance through environmentally sustainable technologies [1-2]. LCA methodologies can greatly aid decision-making by supporting the selection of preferred paving solutions beyond just their economic impact or expected field performance [3-6]. LCA tools are particularly valuable when evaluating innovative materials containing recycled products, which may be attractive due to their contribution to reducing the consumption of raw and non-renewable resources [3-6]. Two recycled materials frequently considered in evolving pavement technologies are CR from scrap tires and RAP [7-11]. CR is obtained by mechanically reducing scrap tires in specialized plants [12]. It can be incorporated into asphalt binders using "wet" and "dry" processes. In the wet process, CR is blended into base asphalt, forming Asphalt Rubber (AR), which exhibits high viscosity, improved elasticity, and enhanced ductility [13–15]. The CR content typically exceeds 15% by weight, and the mixture is produced at 180°C before curing, allowing for gap-graded or open-graded mixtures with high binder content. However, AR can also be used in dense-graded mixtures. In the dry process, CR particles are added as part of the aggregate structure, enhancing the mixture's elastic response [9, 16, 17]. Dosages typically range from 1–3% by weight, and the binder content is slightly increased to account for CR's absorption of aromatic oils [18]. RAP is obtained by milling damaged pavements for Maintenance and Rehabilitation (M&R) reasons. As partially bitumen-coated aggregates from high-quality sources, they can be recycled through cold or hot processes [16, 17, 19]. Research shows that significant RAP quantities can be used without compromising performance [1, 6, 20]. RAP recycling also offers an effective solution for sustainable resource use and waste management [5, 11, 21].

This study assesses the environmental impacts of incorporating recycled materials in asphalt pavements for road surfaces. Both the advantages and disadvantages of these materials were analyzed using LCA, adhering to the guidelines set by the European Commission (2010) [22] and ISO 14040

(2006) [23] standards. The LCA quantified the environmental performance through selected impact indicators. In addition, laboratory testing was conducted on a road project in Iraq, where eleven different asphalt mixtures, including virgin, RAP, and CR were evaluated for the wearing surface. The AASHTOWare software was employed to assess the performance of these mixtures. Finally, the study examined the environmental outcomes of integrating recycled materials into bituminous mixtures for road surfaces.

II. GOAL AND SCOPE

A. Methodology

The research methodology, shown in Figure 1, evaluates the effectiveness and sustainability of incorporating recycled materials into asphalt pavements. The method begins by classifying resources into virgin and recycled categories, with recycled materials consisting of RAP (10%–100%) and CR (10%–50%) in varying proportions. These components are mixed with virgin binders, fillers, and aggregates to generate various asphalt mixtures.

The procedure includes comprehensive laboratory testing to evaluate binder characteristics, Marshall stability and flow, void analysis, and indirect tensile strength. These mixtures were then applied to a case study on Expressway No. 1, Section R9 in Iraq. Utilizing these findings, an LCA is performed with SimaPro 9.3 (2023) to quantify greenhouse gas emissions and evaluate the environmental impact. Furthermore, performance assessments are conducted with the AASHTOWare software. The integration of laboratory, field, and software-based investigation facilitated the identification of optimal recycled material proportions, leading to recommendations for sustainable pavement design.

B. Functional Unit and System Boundaries

The functional unit in this analysis was a 5 cm surface layer of pavement subjected to milling and overlaying. The unit's width and thickness varied according to specific project data and paving scenarios. The LCA covered all processes involved in raw material extraction, composite material production, construction, and maintenance throughout the pavement's service life. Raw material acquisition included:

- Aggregate extraction (blasting, milling, and separation in quarries).
- Bitumen production (refining processes).
- CR processing (mechanical treatment of scrap tires).
- RAP recovery (milling damaged pavements).

Composite material processing was analyzed in hot mix plants, including:

- Bitumen heating and pumping.
- Aggregate feeding and drying.
- Mixing operations (pugmill batch-type production).

The study also accounted for material transportation to production and construction sites. The initial construction phase considered conventional paving and compaction operations using standard pavers and rollers. In contrast, the maintenance phase involved repaving, waste disposal (old pavement layers), and overlay reconstruction. However, the analysis excluded resource use, environmental impacts, and traffic disruptions at work zones. Although the use phase is crucial in LCA studies, it was omitted due to the lack of valid data for the new materials under investigation.

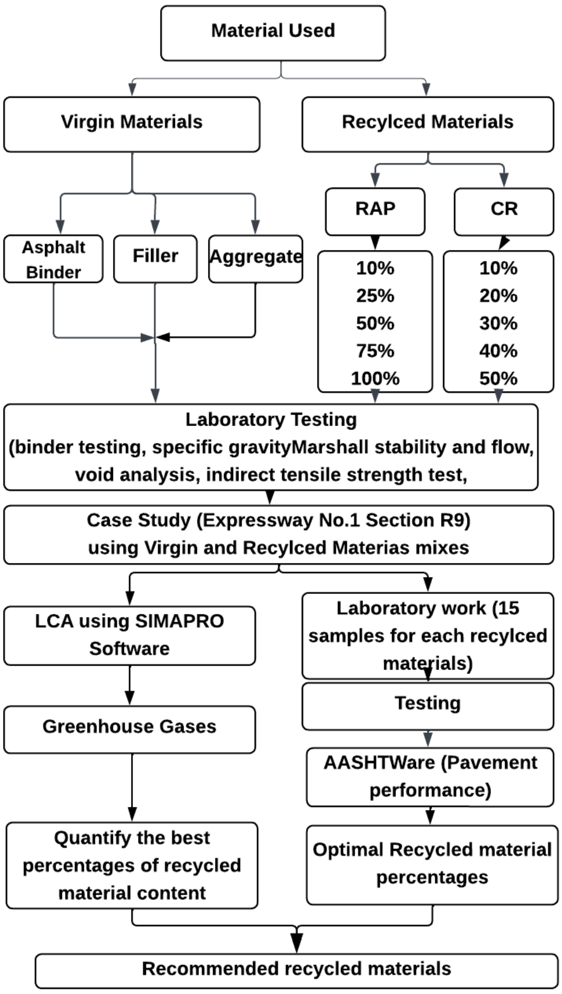

Fig. 1. Research methodology.

C. Trial Sections and Scenarios

The main arterial expressway in Iraq, known as Expressway No.1, connects several regions of the country and stretches from the borders of Syria and Jordan to the border with Kuwait. It is divided into two sections. The first section spans from Baghdad to Safwan (~583 km) and the second section spans from Baghdad to the borders of Syria and Jordan (~615.9 km) [24].

The study focused on Section R9, spanning 123.5 km from western Baghdad to Hit. This roadway has a dual carriageway configuration with three lanes per direction, separated by a 6-meter-wide median. Each lane is 3.75 m wide, and the shoulder is 1.5 m wide. The research analyzed RAP collected from the R9 section through a 5 cm milling process as part of maintenance overlays. The study compared two recycled material scenarios against a control virgin mix:

- Control mix (M_v): Virgin aggregates and binder.
- RAP mix (M_{RAP}): 10%, 25%, 50%, 75%, or 100% RAP replacing virgin aggregates.
- CR-modified mix (M_{CR}): AR binder with 10%, 20%, 30%, 40%, or 50% CR (by weight of total binder).

The control mix (M_v) maintained the same 5 cm thickness as the RAP and CR-modified mixtures. Table I summarizes the unit amounts (kg/m³) of bitumen, aggregates, CR, and RAP used in each scenario. The repair process involved:

- Milling the damaged surface layer.
- Removing and transporting textile waste to a landfill.
- Reconstructing the wearing surface to restore volumetric and mechanical properties.

TABLE I. MATERIALS USED IN BITUMINOUS MIXTURES AND THEIR UNIT AMOUNTS FOR THE ENTIRE SECTION

Scenario	**Quantity (Ton)**				**% Recycled material**	
	Binder	**Aggregate**		**Cement**	**RAP**	**CR**
		Course	**Fine**			
Control mix (standard or virgin HMA) M_v	15.352	163.325	143.726	19.599	–	–
M_{RAP}	15.352	155,158	136,539	19.599	10	–
		142,909	125760	19.599	25	–
		122,493	107,794	19.599	50	–
		102,078	89,828	19.599	75	–
		–	–	19.599	100	–
M_{CR}	13.817	163.325	143.726	19.599	–	10
	12.282				–	20
	10.746				–	30
	9.211				–	40
	7.676				–	50

III. LIFE CYCLE INVENTORY

When conducting LCAs of road pavements, it is commonly acknowledged that Life Cycle Inventory (LCI) data related to construction materials and activities can be incomplete at times. This lack of completeness often necessitates that LCA practitioners rely on estimation methodologies to fill data gaps [17]. For this case study, foreground system LCI data [22] were obtained from the relevant literature and subject matter experts were involved in road construction projects.

Primary electricity consumption data for quarry and hot mix plant equipment were directly collected from a software database as yearly averages, given the limited availability of direct data. Fuel consumption, productivity, and operating hours were also obtained to estimate the impacts of vehicles and machinery used in construction and maintenance. These estimates relied on average hourly fuel usage statistics and reference values [25]. Overall, the LCI process sought to integrate both primary and secondary data to comprehensively characterize the materials and activities involved in the pavement's life cycle.

A. Raw Materials

To initiate the LCA modeling, specific processes were defined, including quarried aggregates, bitumen, RAP, and CR. Energy consumption—including fuel use (L), electricity (kWh), methane (m^3), and CO_2 emissions (kg)—was calculated based on machinery and vehicle usage for production and transport. An existing study on quarries in the Baghdad region, specifically the Al-Nibaae quarry in Al-Taji, was used to gather data on the aggregate output. It was determined that producing 1 metric ton of aggregates requires: 5.3 kWh of electricity, 2.3 m^3 of water, 0.005 L of lubricant oil, 0.002 kg of iron filters, 0.0011 kg of conveyor rubber, and 0.31 L of gasoline. Bitumen data were sourced from the Al-Dora refinery in Baghdad, detailing the LCI of crude oil, including extraction, transportation, and refining. It was estimated that producing 1 ton of bitumen requires: 22.5 kg of natural gas, 50.5 kg of crude oil, 10.9 kg of coal, 0.003 kg of uranium, and 1239 L of water.

The source materials of CR production were surveyed for accessibility in the software. Two transport phases were considered, a) collection of End-of-Life Tires (ELTs) from an average distance of 75 km and, b) delivery of these materials to the processing plant, also 75 km away. Given the processing plant conditions, producing 1 ton of CR requires: 1.45 tons of ELTs with energy consumption accounting to 384 kWh, 2.99 L of diesel oil, and varying but generally around 1.85 kg of "big-bags," 0.29 kg of steel for "shredding blades," 0.22 m^3 of water, and 0.04 kg of "lubricant oil." Additionally, recyclable solid waste from the process includes 0.29 tons of steel and 0.16 tons of textiles. Steel, due to its market value, is expected to be recycled at a 90% rate, while textiles, which can serve as an alternative fuel for cement kilns, are assumed to have a 50% recycling rate. Based on assessments of the milling machine fuel consumption and material transfer to storage sites, RAP data were collected from an existing study on its usage in a road pavement base and foundation courses [16, 17, 26].

B. Composite Materials

The LCA model also included processing units for composite materials, such as bituminous mixes and AR. Information on AR production was sourced from international studies [27] and operational data from selected Iraqi plants. It was estimated that producing 1 metric ton of binder requires 18 L of diesel. Since the AR plant is located in Taji city, Baghdad, it was assumed that the modified bitumen is transported to the Hot Mix Asphalt (HMA) facility by truck with a burner, maintaining a temperature of 180°C.

Data on energy consumption for hot mix plant production were retrieved from an Al-Taji facility. The annual average for producing 1 ton of bituminous mixture at 160°C is: 9.8 m³ of methane (for drying aggregates), 1 m³ of methane (for heating bitumen tanks) and 4.25 kWh of electricity. For AR mixes, a higher production temperature necessitates increased energy consumption. In the absence of direct data, a 10% increase in electricity use was assumed.

C. Material Quantities and Transport

Table II depicts the quantities of the various component materials that make up the layers of a unit-length section of pavement, as well as the average haul distances estimated from production sites to the contraction sites. The overall energy usage was computed utilizing these details in conjunction with the LCI data.

TABLE II. THE TOTAL QUANTITIES AND THE DISTANCES FOR ALL SCENARIOS

Materials	**Scenario**								
	M_v			**M_{RAP}**			**M_{CR}**		
	Transport distance (km)	**Electricity (kW/t)**	**Lorry (freight transport) (ton/ km)**	**Transport distance (km)**	**Electricity (kW/t)**	**Lorry (freight transport) (ton/ km)**	**Transport distance (km)**	**Electricity (kW/t)**	**Lorry (freight transport) (ton/ km)**
Mixture	148.2	8.7	0.24	148.2	8.4	0.24	148.2	9	0.24

D. Construction and Maintenance Phases

Considering an average transport distance of 123.5 km, the fuel consumption for moving composite materials from the plant to the construction site was estimated for both initial construction and maintenance activities. Laying operations were incorporated into the LCA model, capturing the time required for each process and the hourly diesel fuel consumption (FC_h) of construction equipment, as recorded in the program. Authors in [28] present fuel consumption per kilogram of laid, compacted, and milled material (FC_k). This included fuel consumption associated with the reconstruction of the surface course, milling off the old, damaged surface layer (assuming a productivity rate of 150 tons/hour), and transporting this removed material either to a dump or storage, which is roughly 60 km away. The overall consumption was calculated during the entire pavement life span based on the estimated maintenance cycle frequencies in [28].

IV. PERFORMANCE ANALYSIS

A. Materials and Testing

In this research, a combination of virgin and recycled materials was utilized. The materials included asphalt cement, mineral aggregate, filler, RAP, and CR. The use of these materials allowed for the evaluation of different asphalt mixtures in terms of both performance and sustainability, contributing to a comprehensive analysis of pavement rehabilitation strategies. Each material will be summarized separately to provide a clear understanding of its role and properties in the mixtures as follows. For this study, 40/50 penetration grade neat asphalt cement from the Al-Dora refinery was used. Table III illustrates the results of traditional asphalt tests on the neat asphalt binder conducted for an evaluation of the physical and rheological conditions through tests performed by the SCRB specification [24].

TABLE III. PHYSICAL ATTRIBUTES OF THE NEAT BITUMEN USED

Property	**Unit**	**ASTM designation-2015**	**Test results**	**SCRB specification [24]**
Penetration @ 25 °C, 100 gm., 5 sec.	0.1 mm	D-5	46	40-50
Rotational visco-meter,	Pa.s	ASTM D-4402	0.551	
Viscosity @			0.184	
135 °C				
165 °C				
Softening point (ring and ball)	°C	D-36	55	
Ductility @ 25 °C, 5 cm/min	cm	D-113	130	>100
Flash point	°C	D-92	253	>232
Specific gravity	-	D-70	1.023	
After thin film oven test (ASTM D-1754,2015)				
Retained penetration	%	D-5	62	>55
Ductility @ 25 °C, 5 cm/min	cm	D-113	79	>25

1) Mineral Aggregate

In the HMA, the aggregates are quite important. The Al-Nibaae quarry in Al-Taji, Baghdad, was used to obtain crushed aggregates, both fine and coarse. The components that make up coarse aggregate are long-lasting, strong, and tough. According to the SCRB [24], the coarse aggregate gradation can range from 19.0 mm to a 4.75 mm sieve size, whereas the fine aggregate gradation can range from passing through a 4.75 mm sieve to staying on a 0.075 mm sieve. Tables IV and V detail the chemical composition and physical properties of Al-Nibaee aggregate, respectively. All testing listed in Table II took place in Mosul, Iraq, at the National Center for Construction Laboratories and Research.

TABLE IV. CHEMICAL COMPOSITIONS OF SELECTED AGGREGATE

Chemical compound	**Content (%)**
SiO_2	82.52
CaO	5.37
MgO	0.78
SO_3	2.7
Al_2O_3	0.48
Fe_2O_3	0.69
Loss on Ignition (L.O.I.)	6.55
Total	99.09
Mineral composition	%
Quartz	80.3
Calcite	10.92

2) Mineral Fillers

Portland cement, a popular mineral filler used in HMA mix production, is dry and free of particles and clumps. Figure 2 displays the physical parameters and chemical composition of Ordinary Portland Cement. Mosul, Iraq's National Center for Construction Laboratories and Research was the site of these evaluations. These tests are performed in accordance with ASTM D242/D242M [29].

TABLE V. PHYSICAL PROPERTIES OF AGGREGATE

Property	**Unit**	**ASTM designation-2015**	**Result**	**SCRB Specification [24]**
Coarse aggregate				
Bulk specific gravity	-	c-127	2.647	
Apparent specific gravity	-	c-127	2.653	
Percent water absorption	%	c-127	0.57	
Percent wear (Los Angeles abrasion)	%	c-131	23.1	30 Max
Percent soundness Loss by sodium Sulfate solution	%	c-88	3	12 Max
Percent flat and elongated particles	%	D-4791	1.60%	10% Max
Percent fractured pieces	%	-	97%	95 Min
Fine aggregate				
Bulk specific gravity	-	c-128	2.63	
Apparent specific gravity	-	c-128	2.668	
Percent water absorption	%	c-128	0.66	
Mineral filler				
Bulk specific gravity	-	c-128	3.315	
Mineral filler passing sieve no. 200	-	-	96	

TABLE VI. THE CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF ORDINARY PORTLAND CEMENT

Chemical compound	**% Content**
SiO_2	21.51
CaO	62.52
SO_3	1.58
Al_2O_3	5.64
MgO	3.77
Fe_2O_3	3.35
L.O.I.	1.34
Total	99.44
Physical properties	
Bulk specific gravity	3.120
Mineral filler passing sieve no. 200 (C-128)	96
Surface area (m2/kg)	350

TABLE VII. PROPERTIES OF CR

Specifications	**Result**
Color	dark
State	Solid
Density	0.34–0.35 (g/cm^3)
Specific gravity	1.10–1.15
Particle size	0.18–0.6 mm

3) *Recycled Crumb Rubber*

Recycled CR is an elastomer polymer made from recycled tires that has been cut into small pieces, grounded into a powder, and then mixed with neat asphalt binder. Table VII lists the characteristics of the CR modifier. In this research, the particle size used was 0.18–0.6 mm (fine), which is often in wet process modification.

4) *Reclaimed Asphalt Pavement*

RAP from the milling process was used directly. The aggregate materials in this asphalt contain siliceous substances, mixed with 40-50 penetration grade asphalt during preparing the Marshall mixes. The asphalt content of RAP remains unchanged after separating the aged asphalt from the aggregate materials using benzene.

B. *Aggregate Gradation*

The overall gradation used in this research was in line with the gradation standards set by the SCRB [24] specifications for surface layer, with a nominal maximum aggregate sieve size of 12.5 mm. The coarse aggregate gradation falls within 19.0 mm to 4.75 mm sieve size and the fine aggregate gradation, ranging from passing the 4.75 mm sieve to retaining on the 0.075 mm sieve, are presented in Table VIII and Figure 2, respectively.

TABLE VIII. SELECTED AGGREGATE GRADATION

Property	**Unit**	**ASTM designation-2015**	**Result**	**SCRB specification [24]**
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Fine aggregate				
Bulk specific gravity	-	c-128	2.63	
Apparent specific gravity	-	c-128	2.668	
Percent water absorption	%	c-128	0.66	
Mineral filler				
Bulk Specific Gravity	-	c-128	3.315	
Mineral filler passing sieve no. 200	-	-	96	

V. AASHTOWARE INPUTS AND DESIGN CRITERIA

The application of the AASHTOWare design, integrated with laboratory tests, forms a critical pathway toward sustainable and cost-effective infrastructure solutions. Early laboratory tests can ensure that materials meet performance specifications so that premature failure is minimized. AASHTOWare supports data-driven decisions for pavement life cycle alternatives with predicted performance effects, which enables engineers to design pavements able to sustain traffic loads while conserving resources and incorporating recycled materials, such as RAP and CR. This approach ensures reliable pavement performance, long service life, lesser maintenance, and thus, a cost-effective and efficient road network.

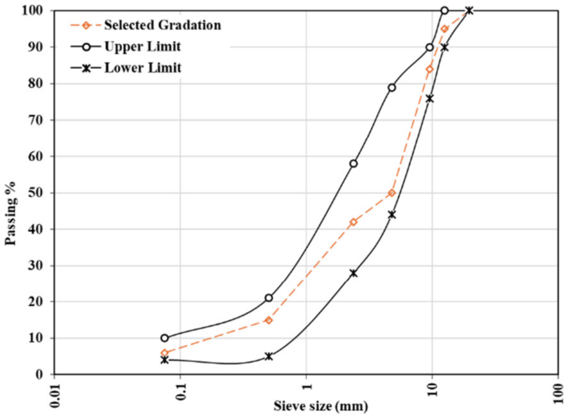
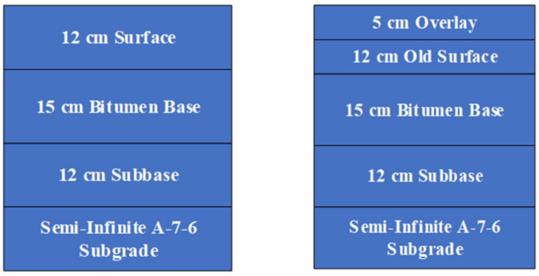


Fig. 2. Aggregate gradation distribution.

The modeling of virgin and different RAP-CR mixtures will give insights into performance indicators, like rutting, cracking, and fatigue life, using field data, such as traffic loads, temperature, and moisture conditions from Iraq. The framework will allow for a meaningful comparison between conventional and recycled asphalt mixtures. The Mechanistic-Empirical Pavement Design Guide (MEPDG) in AASHTOWare V2.3 helps correlate pavement deterioration to asphalt layer thickness. The study seeks to address a 5 cm overlay on Iraq's Expressway No. 1, Section R4/B, including the milling of 5 cm from the top layer to extract RAP. The pavement structure for MEPDG analysis will contain 12 cm HMA, a 15 cm bitumen base, 20 cm of subbase, and an infinite A-7-6 subgrade length, as portrayed in Figure 3. The design level is calculated based on a traffic volume of 15 million Equivalent Single Axle Loads (ESAL).

The change in the variation of recycled materials on pavement distresses was tested for a period of 20 years to establish a baseline for the study. Major indicators of performance were a) resistance to asphalt layer rutting, b) overall pavement rutting, c) top-down cracking, d) alligator (bottom-up) fatigue cracking, and e) top-end smoothness (International Roughness Index (IRI)). The current MEPDG version does not consider reflection cracking, due to the current lack of validation of performance models. The performance evaluation criterion on the MEPDG defaults for roughness setting and limits on design and distress values is shown in Table IX, which evaluates the impact of modification variation upon pavement thickness.

In addition to other information, such as binder penetration and air voids, the laboratory test was conducted to determine the elastic modulus for the new overlay. For the conventional pavement section, the elastic modulus of the base layer was determined using the laboratory indirect tensile stiffness test, as defined for each binder and base course in [22]. The properties for the wearing course and underlying layers (subbase and subgrade) were assumed to be consistent across all pavement sections, as outlined in [25] and presented in Table X. This research modeled all pavement layers as linear elastic materials and subjected to identical loading conditions (single load).



a. Existing b. Applying a 5 cm overlay

Fig. 3. Existing and expected pavement structure.

TABLE IX. M-E PAVEMENT DESIGN CRITERIA

Design criterion		Design information	
R (%)	90	Base construction	Jul-24
IRI^{o} (m/km)	1	Pavement construction	Sep. 2024
Terminal IRI (m/km)	2.71	Traffic opening	Nov. 2024
Top-Down fatigue cracking (m/km)	379	Climate data sources	(Houston,TX (12960) *
AC bottom-up fatigue cracking (%)	25		
Thermal cracking (m/km)	189	Assumed total ESAL	15×10^{6}
Permanent deformation (AC Only) (cm)	0.63		
Permanent deformation (Total) (cm)	1.9	Annual Average Daily Traffic (AADT) (veh./day)	10,000

*The climate station chosen in the present study was Taxes since this area is close to the Iraq weather.

TABLE X. PROPERTIES OF CONVENTIONAL HMA USED FOR ESTIMATION THICKNESS REDUCTION

Layer	Thickness (cm)	Poisson's ratio	Elastic modulus (MPa)	Ref.
Wearing course	5	0.35	1194	Lab. results
Binder and base (stabilizer) courses	7.15	0.35	2609	[22]
Subbase course (granular material)	20	0.4	104	[25]
Subgrade	-	0.5	40	[25]

In addition, other medium traffic scenarios were devised for designing new pavements, as evidenced in Table XI. A particular point of analysis was the truck traffic classification for expressways (TTC1: bus > 2%, multi-trailer < 2%, mostly single-trailer trucks) with default vehicle class distributions and axle load spectra (level 3 input). Traffic data for the design's 20-year period were converted into an equivalent number of 18-kip (80-kN) single-axle loads (18,000-pound ESAL), using the load equivalent factor from the AASHTO 1993 pavement design guide for comparative purposes.

TABLE XI. DATA RELATED TO TRAFFIC VOLUME

	Medium traffic level
Assumed total ESAL	15×10^6
AADTT (veh./day)	10,000
Design speed (km/h)	80
Truck in design direction (%)	50
Truck in design lane (%)	95
Growth rate	4%

VI. RESULTS AND DISCUSSION

A. *Effect of Surface Rutting*

To predict rutting in asphalt overlays, the relationship between laboratory tests and modeling must be scientifically determined. Rutting is primarily affected by material properties, mixture design, and traffic response. Each configuration, whether virgin overlays, CR-modified binders, or RAP, will behave differently in terms of rutting based on structural and material composition.

Virgin asphalt overlays with a layer thickness of 5 cm in binder aggregate, show lower initial rutting than cases where materials met all specifications. However, deformations under high traffic or higher temperatures could be very serious with these systems. The addition of CR is inversely proportional to Marshall stability (10-50%). Models have shown that there is significant stability between 30-40% CR content when workability and compaction are not an issue. RAP softens asphalt mixtures, providing a filler effect to the binder due to its pre-aged character, thereby reducing rutting at moderate levels (10-50%). Then a risk develops when the RAP content exceeds 75% to nearly 100%, as it becomes an embrittled mix unless softened by additives or softer virgin asphalt base powders.

Figure 4 illustrates the trends of rutting with changing configurations. Virgin overlays experience the greatest rutting, while CR-modified binders improve to an optimal level. RAP shows reductions in rutting due to more irreversible bearing with up to 50% content; beyond this, increased brittleness develops. These trends highlight the importance of balancing mix components for optimal pavement performance.

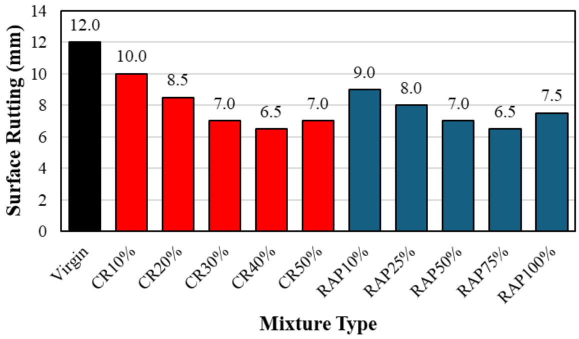


Fig. 4. Effect of virgin, RAP, and CR on surface rutting.

B. *Effect of Bottom-Up Cracking*

Bottom-up cracking occurs when tension stresses build up at the bottom of the asphalt layer under repeated traffic loads. Predicting this behavior in virgin overlays, CR-modified binders, and RAP aggregate replacements requires knowledge of the materials' moduli, the binders' elastic behavior, and the asphalt's ability to relieve tensile stresses. Virgin mixes moderately resist bottom-up cracking if the binder and aggregate meet specifications. However, these mixes are prone to fatigue under heavy or repeated loads due to a lack of improved elasticity and self-healing properties. CR-modified binders (10-50%) enhance these properties, with 10-30% CR content improving elasticity and stress dissipation, whereas 40-50% CR content increases stiffness, reducing these benefits and making the mix more prone to cracking. RAP aggregate replacement increases mixture stiffness due to aged asphalt on RAP particles. Low RAP content (10-25%) balances stiffness and flexibility, reducing bottom-up cracking. Higher RAP percentages (50-100%) excessively stiffen the mix, leading to greater tensile stresses and faster fatigue. Blending with soft virgin binders or rejuvenators can improve cracking resistance from excess stiffness. The results are presented in Figure 5.

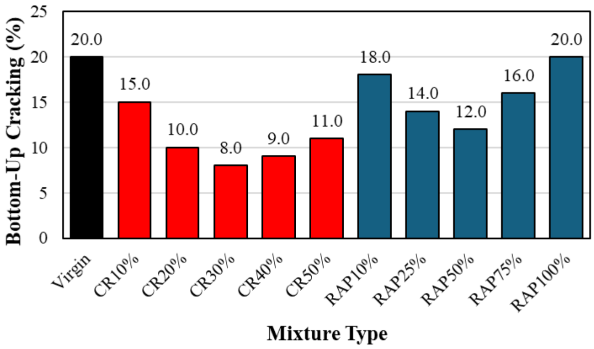


Fig. 5. Effect of virgin, RAP, and CR on bottom-up cracking.

C. *Effect of International Roughness Index*

IRI assesses the ride quality of asphalt pavements in terms of smoothness and comfort based on the material and construction quality and their long-term performances. Factors, such as virgin overlays, CR-modified binders, and RAP aggregate replacements, considerably affect the IRI, while construction techniques facilitate the maintenance of smoothness under traffic, deformation, and over time.

Compaction of virgin overlays may yield a low IRI with quality materials. However, over time, this degrades under traffic, increasing IRI due to cracking, rutting, and surface distresses, as can be seen in Figure 6. CR-modified binders improve durability against deformation, especially with 10-30% CR content, lowering IRI. Higher CR content (40-50%) increases stiffness, hindering the mixture's ability to absorb traffic stresses, leading to localized roughness and increased IRI.

RAP replacement affects IRI by balancing stiffness and flexibility with low RAP content (10-25%), which helps maintain an even surface and low IRI. High RAP content (>50%) increases stiffness, brittleness, and surface irregularities, raising IRI. Combining RAP with rejuvenators may reduce binder stiffness and improve flexibility, ensuring smoothness and ride quality throughout the pavement's lifespan.

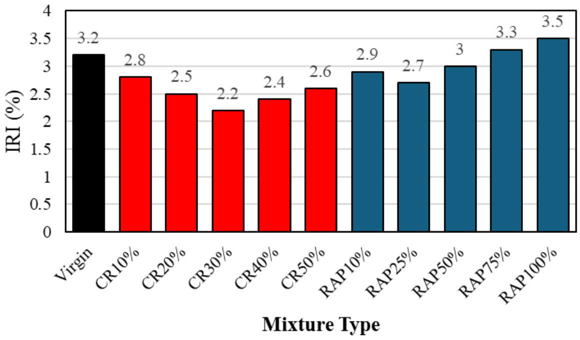


Fig. 6. Effect of virgin, RAP, and CR on IRI.

D. *Expected Service Life*

The longevity of asphalt pavements depends on their ability to resist rutting, cracking, and wear under traffic and environmental conditions. Therefore, establishing durability and strength for fatigue, cracking, and deformation of virgin overlays, CR-modified binders, and RAP aggregate replacements is essential for performance predictions.

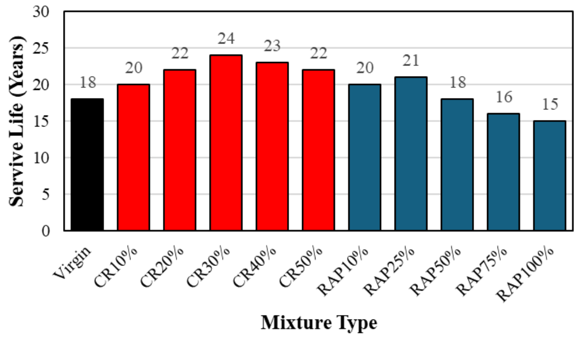


Fig. 7. Expected service life of using virgin, RAP, and CR overlay.

Virgin overlays (≤5 cm thick) exhibit a 15–20 year lifespan under normal traffic and maintenance conditions, as depicted in Figure 7. While they have a smooth surface initially, they lack high temperature slip resistance and self-healing characteristics, making them more susceptible to cracking and rutting under heavy loads and harsh climates. CR-modified binders (10-50% CR) enhance asphalt durability by improving flexibility and reducing cracking. 10-30% CR content increases elasticity and stress dissipation, extending service life. At 40-50% CR, increased stiffness improves wear resistance, but flexibility is reduced, limiting further benefits. RAP aggregate replacements improve durability. Low RAP content (10-25%) offers a good balance between stiffness and flexibility, providing a lifespan equal to or better than virgin overlays. Higher RAP content (50-100%) increases brittleness and leads to early cracking. Blending RAP with softer binders or rejuvenators can improve flexibility and prolong pavement life.

E. *Life Cycle Cost Analysis*

Given the significant annual investment and large energy and natural resource usage for pavement M&R activities, environmental improvement and cost savings can be achieved through eco-friendly and cost-effective scheduling decisions. Typically, M&R schedules are optimized based on LCCA [30].

Cost analyses were performed for three surface asphalt mixtures: virgin asphalt, mixtures with varying RAP proportions, and mixtures incorporating recycled rubber at different percentages. The construction costs were derived from municipal and market prices, including material extraction (both virgin and recycled), mixing, transport, and compaction costs for each mixture type. The project maintenance costs were incorporated, based on an estimated maintenance cycle of every five years for a 15-year road lifespan. The user and traffic delay costs were excluded due to limited data.

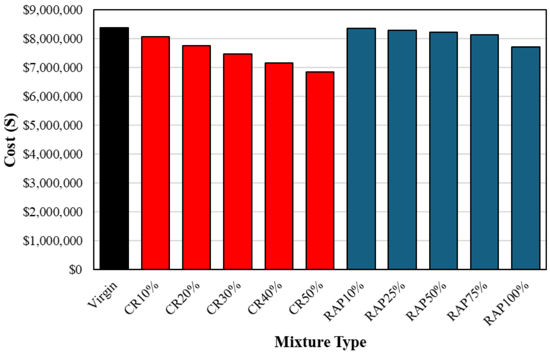


Fig. 8. Cost for virgin, RAP, and CR in the 5cm overlay layer construction stage.

Figure 8 presents a cost comparison for all alternatives, showing that costs decrease as the RAP and rubber content increase compared to virgin asphalt. This indicates economic benefits and environmental advantages when utilizing recycled materials in asphalt mixtures.

VII. CONCLUSION

This research highlights the performance and sustainability benefits of using Reclaimed Asphalt Pavement (RAP) and Crumb Rubber (CR) in asphalt mixtures. The cost analysis demonstrated significant savings in construction and maintenance, reinforcing the use of recycled materials for sustainable paving solutions. Mixtures with higher percentages of RAP and CR were more cost-effective than virgin materials, proving the economic viability of integrating recycled materials into asphalt mixes.

Performance predictions using AASHTOWare showed that incorporating recycled materials enhances pavement durability by reducing rutting and cracking under traffic and environmental stresses. The optimal mixtures of RAP and CR are predicted to have a much longer service life than traditional virgin asphalt overlays. AASHTOWare also indicated that recycled asphalt mixtures require less maintenance over twenty years, even under realistic traffic and climate conditions, making them suitable for large-scale applications. Overall, the research confirms that incorporating 50% RAP and 30% CR provides the best balance of mechanical performance, environmental sustainability, and cost efficiency, supporting the potential of recycled materials in creating more sustainable and affordable paving solutions.

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