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Lifecycle Analysis of Recycled Asphalt Pavements: Case Study Scenario Analyses of an Urban Highway Section

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Abstract: Roads account for a major part of energy/resource consumption and emission of GHGs, such as CO_2, PM, NO_x, O_3, etc., due to high demand for virgin materials, specifically in developing regions. The applicability of recycled materials, such as recycled asphalt pavement (RAP) and other alternative approaches for, e.g., warm-mix asphalt (WMA), in developed countries is hindered by project-specific constraints and lack of empirical studies in these regions. Lifecycle assessment studies on the usage of these road options from actual projects in the developing countries can aid decision makers choose sustainable material approaches by providing case study examples as guidelines. To that end, this study analyses environmental in/out-flows for a traditional approach and multiple green approaches (RAP and WMA) for a major highway section in Abu Dhabi through a 30-year (2015–2045) lifecycle approach. Roadworks were modelled in SimaPro according to real-world conditions, and the expected burden mitigation in each stage is calculated. Benefits of using optimum RAP-based options and a virgin-material-based WMA case against the baseline virgin material case were also investigated. Results showed benefits of WMA as higher than replacing virgin asphalt with recycled asphalt (25% RAP asphalt base, 15% RAP binder and wearing courses). Land use (19%) and energy consumption (16%) showed the highest reduction, followed by ozone depletion (14%), ionizing radiation (11%), PM (8%), acidification (7%) and global warming potential (6%) across all pavement lifecycle stages and environmental indicators. Similar results were obtained for other scenarios with lesser degrees of reduction, which show the significance of replacing HMA with WMA for real-world projects, specifically in mega road projects in Abu Dhabi and the Middle East towards cutting the significant carbon footprint of asphalt pavements.

Keywords: lifecycle analysis; highways; scenario analyses; warm-mix asphalt; road construction

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1. Introduction

Several problems are associated with the current road transport systems due to the demand and consumption of virgin materials for construction and maintenance and rehabilitation (M&R) activities that extend over the entire lifecycle of roads. The service life of any built asset starts from the conceptual stage to extraction of raw materials, construction, use, M&R and the final end-of-life stage that itself may be composed of recycling and disposal [1]. Typically, the environmental impacts of material processing, concrete works associated with roads (barriers, kerbs, foundations for traffic lights and signs) are not modelled in road and pavement sustainability or lifecycle assessment (LCA) studies. Environmental emissions from diesel fuel consumed during equipment (wheel loaders, dump trucks, air compressors, compactors and track-type tractors, etc.) transport by road to site are not traditionally calculated by existing LCA literature. However, this work argued that these are an essential part of the real-world roadworks tendering and construction process and may influence the ability of local decision makers to estimate the environmental impact of the entire construction process.

The majority of current research on LCA of roads has either focused on material type (e.g., asphalt vs. concrete pavements) or only pavement overlay, disregarding the whole structure. While defining the goal and scope of a roadwork asset investment, it may not be sufficient to constrain the debate to material type or pavement surface. The application of LCA for assessing the potential of recycled material usage and industrial by-products for roadworks has recently been given considerable attention by researchers [2,3].

Biswas [4] found that using 15% recycled asphalt pavement (RAP) and 50% RAP as partial replacement of virgin asphalt in base course during maintenance and rehabilitation only showed that 10 tonnes CO_2 eq. (7%), 39 tonnes CO_2 eq. (27.1%) were noted compared to the 738 tonnes CO2 eq. from the virgin asphalt pavement option. However, the replacement of virgin materials in the wearing course was not analysed, and impacts were assessed only for the hot-mix asphalt option. Furthermore, the study only compared the environmental impacts in limited lifecycle stages, notably disregarding earthworks, even though it is a significant part of lifecycle studies in other construction works [5].

Turk et al. [6] and Bloom et al. [7] also explored the partial and complete replacement of natural aggregate base course with recycled construction waste (RCW) to varying degrees of GHG reduction. Bloom, Canton, Ahlman and Edil [7] assessed the environmental benefits of RAP usage during the M&R stages of asphalt pavements in their United-States-based study. The authors employed a 4% replacement of the asphalt binder content by RAP and observed a significant reduction in GHG emissions. However, effectively communicating the benefits of sustainable road construction techniques, particularly recycled material usage, and usage-stage savings to the other decision-making stakeholders is also important for direct application in real-world situations [8,9].

Since every stage during the life of a product involves energy input/outputs (I/Os) and resource consumption, any comprehensive study aiming to address the issue of sustainability and environmental impacts must acknowledge the process flow over the entire cycle of the supply chain [10,11], thereby reducing a "shifting of issues" from one phase or ecosystem to another, given the phases in a product's lifecycle consist of several intermingled loops. In the so-called product life, sustainability starts from planning and design in the conceptual stage to the subsequent construction to EOL stages [12]. These environmental impact issues are arguably more addressable in the initial stages of road lifecycle.

Additionally, even though the design and development stages of any road may not cause higher lifecycle environmental impact, it may be significant for determining as well as reducing impacts in the subsequent stages, as illustrated in Figure 1. This figure is based upon the study by Rebitzer et al. [9], which also modelled the minor environmental impact from design and development stage of roads, such as electricity and other resources consumed to create road design plans, but these impacts are not considered part of the system boundary here, as it is focused on cutting impacts from using recycled materials for roadworks. Nonetheless, their finding implies that choosing the optimum recycled material option in the pre-construction and construction stages might be more beneficial than usage in the M&R stages. Over the years, several studies have attempted to assess the environmental impact of using recycled pavement materials in at least one of the lifecycle stages using LCA methodology to some extent. Some of these significant studies over the past two decades focusing on recycled pavement material usage are covered in Table 1.

Table 1. Scope and methodology of selected LCA-based studies on roadways and pavements over the last 20 years [1].

Researchers	Lifecycle Stages Addressed [2]	Research Outcome	Limitations
Park et al. [13]	- RME and P - Construction - M&R - EOL	- M&R predominantly contributed to the lifecycle GHG emissions and energy consumption (2676.8 tonnes of oil equivalent/km). - Local material availability was important in material selection, yet local supply chain was lacking in the study.	- Transportation of extracted and processed material was disregarded. - Road concrete works emissions not calculated. - Material transport to site was disregarded.
Birgisdottir et al. [14]	- RME and P - Construction - O and U - M&R - EOL	- Environmental benefits gained from use of recycled bottom ash found to be balanced by landfilling. - Groundwater contamination may occur due to leachate from salting of roads, as an environmental side effect. - Local material supply chain had a significant impact on material choice, as well as environmental emissions.	- Limited alternative pavement material options analysed. - Warm-mix asphalt and wearing course RAP usage not analysed. - Material transport to site was disregarded.
Oliver-Solà et al. [15]	- RME and P - M&R - EOL	- Environmental impacts noted for slabs were irrespective of their thickness. - Cement usage accounted for 24–77% of the environmental impacts of different sidewalks.	- Only focused on road concrete works. - Material transport to site was disregarded.
Huang et al. [16]	- RME and P - Construction	- Usage of recycled materials was found to influence the environmental burdens noted for the different alternatives.	- Operation, usage, and M&R were not analysed. - EOL recycling disregarded.
Lee et al. [17]	- RME and P - Construction	- Generation of hazardous waste (11%), consumption of water (11%) and energy (16%) and GWP (20%) were found to be reduced due to use of recycled materials.	- As above
Cass and Mukherjee [18]	- RME and P - Fuel - Construction	- Fuel production, material and equipment usage were found to be the major contributors to CO_2 emissions from the construction stage, accounting for 90–94%.	- Fuel production was considered, yet the operation of on-site equipment was not considered. - M&R and EOL were disregarded.
F. Mendoza et al. [19]	- RME and P - Construction - EOL	- Type of construction material was found to be the major contributor to the environmental impacts from the lifecycle of a sidewalk, for example, 76–177% from imported granite usage.	- M&R costs and emissions. - Study was constrained to road concrete works and disregarded the pavement section.
Wang et al. [20]	- RME and P - Construction - O and U - EOL	- Highways with low traffic were found to be influenced by surface smoothness and rolling resistance of wearing course. It was revealed as the major contributor to M&R stage GHG and energy loads.	- Impacts in M&R activities were ignored. - Material and equipment transport to construction site was disregarded.

Table 1. *Cont.*

Researchers	Lifecycle Stages Addressed [2]	Research Outcome	Limitations
Yu and Lu [21]	- Pavement albedo in O and U	- Significant contribution of pavement albedo on the lifecycle impact of the roadway was noticed.	- Disregarded environmental impacts of all other stages.
Biswas [4]	- RME and P - Construction - M&R	- Use of recycled materials during road construction reduced overall environmental footprint. Using 15% RAP, 100% concrete rubble and reused crushed rock base during the M&R phase reduced carbon footprint by 6%. - Local material supply chain was noted as a significant factor.	- Equipment and material transport to site during construction stage and O and U was not considered. - Construction-stage RAP and recycling was not analysed.
Choi et al. [22]	- RME and P - Construction - M&R - EOL	- CRCP was found to be the most sustainable choice compared with JRCP and JPCP.	- Study lacked estimation of emissions during the O and U stage. - Disregarded environmental impact comparison with recycled approaches for asphalt pavements.
Almeida-Costa and Benta [23]	- RME and P - Structural performance during O and U simulated	- Cost and environmental impact of producing virgin WMA was analysed against HMA and resulted in significant reduction in CO_2 and energy consumption without compromising on the structural performance of WMA pavements.	- Environmental impacts over the entire lifecycle of a WMA pavement were not analysed. - Real-world applicability for roadworks was not assessed.
Santos et al. [24]	- RME and P - Construction - O and U - M&R	- Lower environmental impact of WMA using virgin pavement materials compared to virgin HMA is offset by the synthetic hard wax additive. - Using 30% RAP during M&R resulted in environmental impact reduction of up to 29%.	- Comparison of environmental impact reduction using other additives for WMA production, e.g., zeolites, was not considered.
Santos et al. [25]	- RME and P - Construction - M&R - EOL	- Using foam-based WMA containing 50% RAP considerably reduced environmental footprint across all conventional impact categories. - Environmental impact of HMA or WMA pavements was dependent upon the fuel used in the batch-mix asphalt production plant. - Structural performance of alternative-material-based asphalt pavements was lower than the conventional HMA pavements.	- Environmental impacts from HMA using same RAP content as WMA were not analysed to clearly show the benefit of WMA over HMA. - Material and equipment transport to the construction site was not modelled.

Table 1. *Cont.*

Researchers	Lifecycle Stages Addressed [2]	Research Outcome	Limitations
Hasan et al. [26]	- RME and P - Construction - M&R - EOL	- Pavement mixtures containing various proportions of RCW, RAP and WMA were compared against virgin HMA pavements. - The highest environmental impact reduction was for energy consumption at 48%, 34% for global warming potential, NO_x emissions at 34%, and 22% for PM emissions. Lowest for land use (10%) and acidification (20%). - Environmental footprint reduction was only slightly affected by the allocation approach.	- Operation and usage stage was disregarded. - Study lacked comparative LCA results between the pavement mixtures containing same proportion of asphalt between virgin HMA and WMA. - Pavement mixtures containing the same amount of RAP across each layer were analysed without intermediate environmental footprint reduction results.
Vandewalle et al. [27]	- RME and P - Construction - M&R	- HMA mixtures containing 25%, 50%, 75% and 100% of RAP during the M&R stage showed an average reduction of 19%, 23%, 31% and 33% across the studied four environmental indicators.	- Construction-stage impact comparison with RAP content pavements was not assessed. - Material and equipment transport to construction site was disregarded.
Bressi et al. [28]	- RME and P - Construction	- Partial replacement of virgin HMA with RAP content caused reduction in environmental footprint. - Pavement mixture containing up to 80% RAP with specialised local additives reduced energy consumption by 18% (900 MJ/ton) and global warming potential by 15% (18 kg CO_2 eq./ton). - Crumbed rubber caused an increase in environmental impact.	- Site clearance and equipment transport were not analysed as part of the LCA. - Results were highly dependent on the specialised additive, and its applicability to other projects in different regions might be affected due to material supply chain. - Comparison with WMA for same recycled materials was not explored.
Lu and Nguyen [29]	- RME and P - Construction - M&R - EOL	- Structural performance of WMA with 20–50% RAP, produced with antistrip additive, was similar to HMA pavements. - Energy consumption of the RAP-based WMA was 17.8% to 28.7% lower, and global warming potential was 16.6% to 27.0% lower than the HMA pavements.	- Impacts during construction stage using same RAP content in HMA pavements was not compared with RAP-based WMA pavements. - Equipment transport to construction site was not assessed.

[1] ***Key:*** GPW = global warming potential, JRCP = jointed reinforced concrete pavement, CRCP = continuously reinforced concrete pavement, JPCP = jointed plain concrete pavement, RCW = recycled construction waste. [2] *RME and P = raw material extraction and processing, O and U = operation and usage, M&R = maintenance and rehabilitation stage, EOL = end-of-life.*

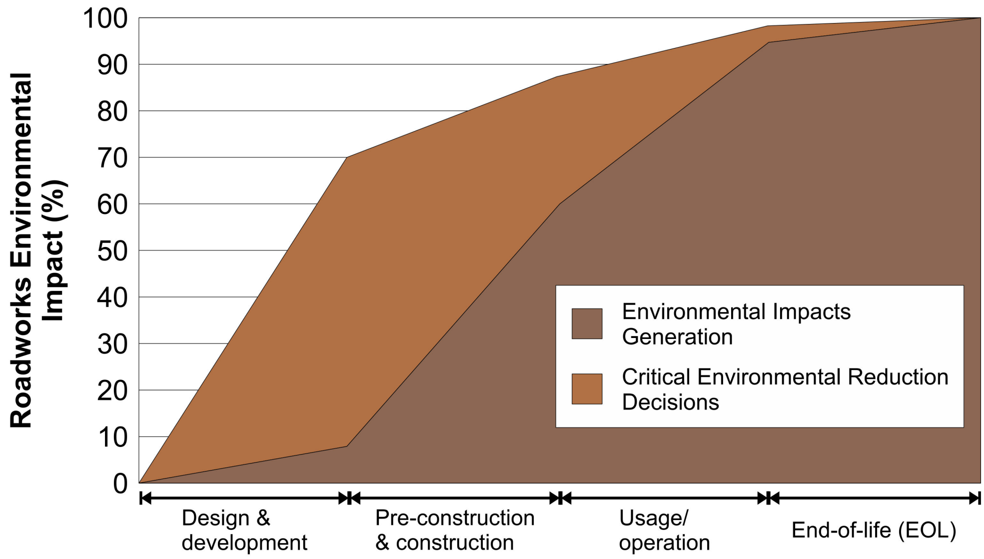

Figure 1. Roadworks' environmental impacts and potential for impact reduction through decisions across all lifecycle stages (based on Rebitzer et al. [9]).

In addition to the pavement recycled material usage studies covered in the literature in Table 1, some studies also focused on the recycling method and the asphalt production method, i.e., hot-mix against warm-mix asphalt. Due to the focus on recycling road materials and ease of recycling asphalt, several studies on the environmental and mechanical properties of recycled asphalt compared the two recycling techniques: ex situ (in-plant) and in situ (hot > 120 °C, cold 50–120 °C or warm < 50 °C in-place) [16]. The results showed that surface recycling may be adequate for pavements with minor cracks (depth: 25–50 mm). Hafez et al. [30], in a survey of the rehabilitation policies practised by different United States transportation agencies for low-traffic-volume roads, found that hot in-place treatment methods are only marginally applied. Nonetheless, a combination of improved in-place recycling and low traffic volume may further increase the potential benefits from sustainable management practices during the construction and maintenance stages of the lifecycle of such roads [31].

On the other hand, Butt and Birgisson [32] analysed the GHG emissions of the different asphalt mixing techniques and found that warm-mix asphalt has lower per-tonne CO_2 equivalent emission (warm-mix 87 tonne/km compared to 141 tonne/km for hot-mix). However, this on-site and warm-mix asphalt usage is a local factor, and the actual feasibility depends upon the on-site climatic conditions, technology and material/equipment supply chain [33]. Furthermore, Whyte and Laing [34] noted that this variation in environmental impacts also creates difficulty in judging the benefits attainable from usage of greener materials and construction techniques, which may be unique to the geographical region under consideration.

Existing pavement literature covered above shows that the environmental impact reduction performances of any alternative options using recycled materials are dependent upon the local material supply chain, transport distance and other up/down-stream processes in all lifecycle stages of the complete roadworks. There is a lack of lifecycle analysis studies in road literature that account for impacts across pavement courses, roadside concrete kerbs, barriers and foundation works for the traffic signs and lighting systems in a concise work. The feasibility of RAP and WMA for high-environmental-footprint pavements in regions where virgin material usage is rampant also remains unassessed.

The majority of pavement research on RAP and recycled/alternative material technologies has been focused on road projects in the Americas and Europe, which already have high recycled material usage, while little focus has been placed on areas where virgin pavement materials are used to construct roads using traditional the hot mix [26,35].

Studies [36,37] have noted that it is difficult to generalise findings from these Europe- or United-States-based studies to other regions due to differences in energy sources, construction practices and availability of materials. Additionally, transporting material and equipment to construction site might potentially carry considerable environmental emissions due to the usage of heavy trucks and fuel consumption; yet, existing LCA studies on pavements do not account for this issue, even though RAP usage, on-site recycling or differences in equipment operational needs between RAP and virgin asphalt can affect the overall LCA results between the RAP- and non-RAP-based pavement construction options.

Over the last two decades, the United Arab Emirates (UAE) construction market has seen an unprecedented growth with the commencement of ambitious construction projects. Even though it is non-annexure-I country under the Kyoto Protocol, without a legally binding emission reduction target, the local government is focused on monitoring the benefits of GHG-reducing construction practices. It has launched several mitigation measures to reduce these environmental burdens, such as the commitment by Abu Dhabi government to invest approximately USD 60 billion in renewable energy programmes [38]. Nonetheless, the high-paved travel lane (18,965 km urban streets and 2708 km highways), inexpensive fuel, high ridership and vehicle ownership in the Abu Dhabi city has resulted in annual GHG emissions of 11,735.60 Gg CO_2 eq. from road transport systems [39].

Therefore, it is important to understand the sources of emissions and energy consumption from construction and other lifecycle stages of major roads in Abu Dhabi and the neighbouring Gulf Cooperation Council countries. The purpose of this study is to establish precedence regarding the use of recycled/alternative materials and lifecycle research in the United Arab Emirates and the Middle East region, where only few such studies are available. In this study, the impact of using alternative/recycled materials for roads in the UAE is analysed. To address the contribution of virgin asphalt pavement materials and gradually compare the RAP and WMA options, this study presents an LCA methodology to analyse the environmental footprint for a major road project in Abu Dhabi as representative of high-material-demand pavement projects in the Middle East and southeast Asian regions with similar climatic conditions. The findings from this study can then aid decision makers from these regions reduce the environmental impact from roadwork activities throughout the built asset's lifecycle towards applying their respective low-carbon objectives.

2. Methodology

In order to identify the critical impacts for the different available alternatives of any project under consideration, several methods (e.g., EDIP, ReCiPe and midpoint methods in Europe; TRACI in North America and the general CML method) exist based upon the inventory and regional factors for different impact categories. The calculated values can then be aggregated in the regional public databases for use in LCA studies in a particular region, for example the International Reference Life Cycle Data System (ILCD) handbook on best LCA practices [40], Infrastructure Sustainability Council of Australia rating, Eco-points [41], Greenroads and Civil Engineering Environmental Quality guidelines [42]. The existing LCA research used several approaches towards the establishment of a functional unit, system boundary, selecting databases and sources of data collection and life-cycle inventory approach (conventional simplified process LCI, I/O LCI and hybrid LCI). The LCA methodology for this study is explained below for each LCA component.

2.1. Goal and Scope

This study applies lifecycle methodology to calculate the environmental impacts of a 3.5 km-long asphalt dual carriageway section case study in Abu Dhabi. The case study highway section is shown in Figure 2. This 3.5 km pavement is considered a functional unit. Pavement LCA researchers [6] have studied end-of-life pavement base and wearing course rehabilitation after 30 years of construction, and this 30-year period, from 2015 (from initial construction) to 2045, is selected as the lifecycle period based on local guidelines and previous pavement literature.

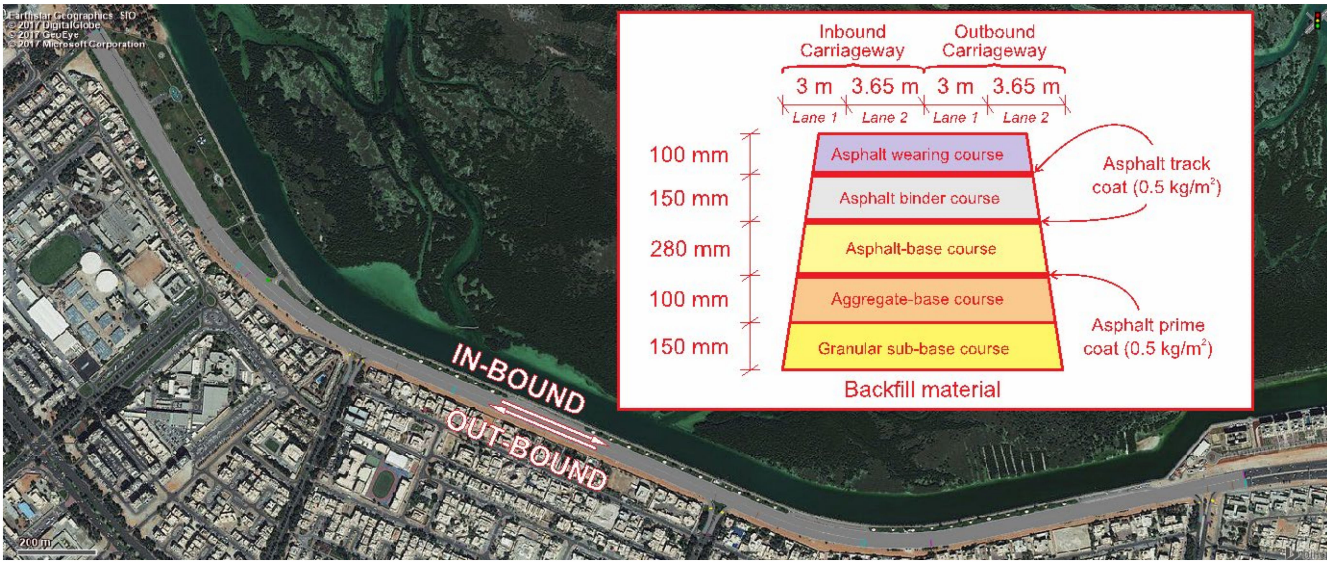

Figure 2. Case-study asphalt pavement section.

Thus, for this study: *Goal*; comparison of sustainability performance of traditional approach and two green approaches of pavement from recycled material (RAP) and WMA pavements. *Scope*; Initial site clearance, raw material extraction, production and processing, infrastructure construction, maintenance and end-of-life. Operation and usage stage is not considered, since past research has shown that the majority of environmental footprint from this stage is due to vehicle fuel consumption [43]. Nonetheless, the impact of pavement surface conditions might affect emissions, yet it cannot be modelled in this study due to lack of local pavement–vehicle interaction data.

2.1.1. System Boundary

For this study, the LCA system boundary stretches across the following lifecycle stages: material extraction and production, material and equipment transport, construction, M&R, and end-of-life, assuming a 30-year lifetime. Figure 3 shows the system boundary considered in this study.

Environmental impact assessment is performed for air emissions and energy consumption by complete roadworks: earthworks, pavement courses, concrete works for traffic barriers, kerbs, parapets, traffic signs and light systems. Actual field data for the road section using virgin materials and traditional asphalt production mix for pavement works and Portland cement concrete for the complete concrete works are used as the baseline case. The impacts of using different percentages of RAP (10%, 15% and 25%) and 100% WMA are then analysed as alternative cases. This replacement is gradually applied across all pavement layers to empirically distinguish the benefit of RAP usage in each pavement layer. The pavement alternatives analysed here are:

- Baseline (B): Virgin asphalt pavement section
- Alternative 1 (A1): 10% RAP in HMA wearing course
- Alternative 2 (A2): 10% RAP in HMA base and binder courses
- Alternative 3 (A3): 10% RAP in HMA base, binder and wearing courses
- Alternative 4 (A4): 15% RAP in HMA wearing course
- Alternative 5 (A5): 15% RAP in HMA base and binder courses
- Alternative 6 (A6): 15% RAP in HMA base, binder and wearing courses
- Alternative 7 (A7): 25% RAP in HMA base, and 15% RAP in HMA binder and wearing courses
- Alternative 8 (A8): Virgin WMA in asphalt base, binder and wearing courses

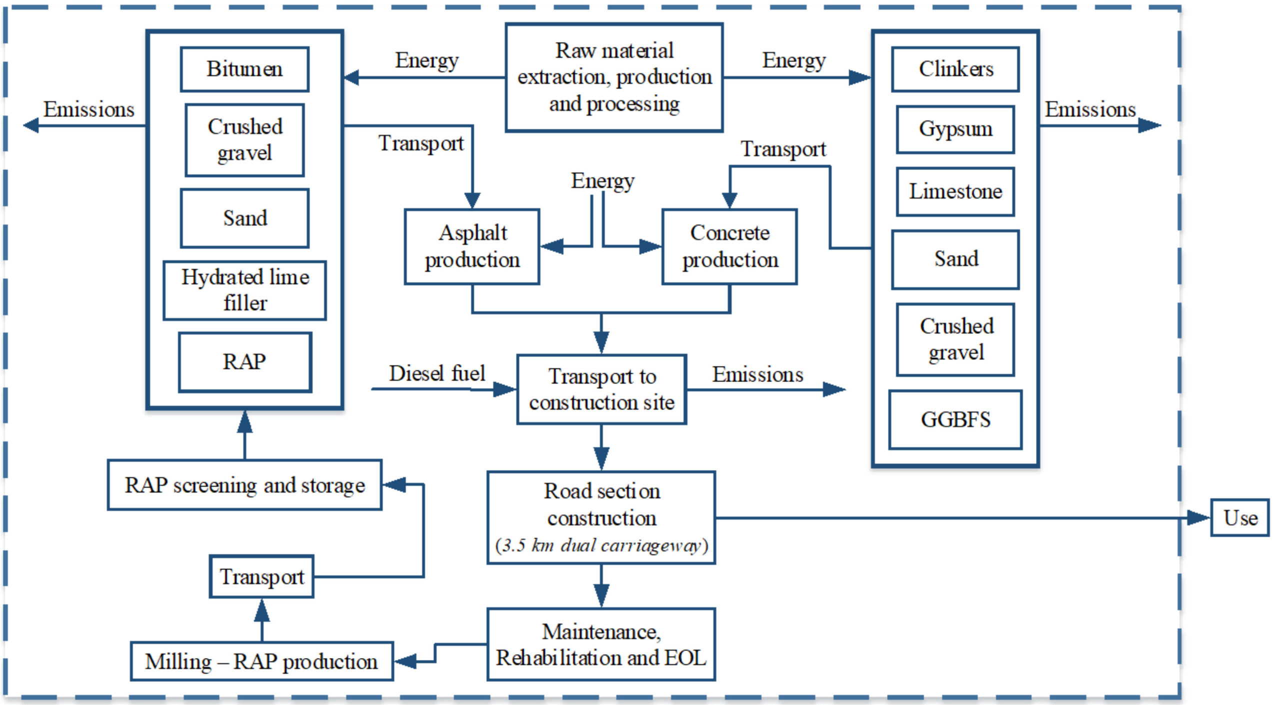

Figure 3. System boundary considered for the studied pavement section.

The environmental assessment is conducted in the lifecycle assessment software SimaPro v8.5.2 [44,45], considering all the indicators from the ReCiPe midpoint method, which was used to calculate the energy consumption and emissions. SimaPro is considered a popular lifecycle assessment tool due to the large material impact library and associated databases, such as Ecoinvent, that can model all upstream and downstream impacts associated with any product [44,46]. It has been applied in many studies around the world analysing the lifecycle environmental impact of pavements, as it can take in multiple supply chain inputs, compensate for missing values and provide environmental impacts in per functional unit for simplified impact assessment across multiple construction and maintenance alternatives [27,47,48]. The ReCiPe midpoint method is applied because it is considered the only lifecycle assessment method applicable for global studies [49]. The database used in SimaPro was Ecoinvent, similar to other pavement studies [27,47,48], with lifecycle inventory and supply chain inputs modified based upon the data for UAE, collected as part of Section 2.1.2. The allocation approach applied was at the point of substitution, which has also been applied by other studies [26,50] and, in simple terms, credits the system for using a recycled material that would have otherwise ended in landfill.

2.1.2. Lifecycle Inventory and Impact Assessment across All LCA Stages

Initially, the aggregate sub-base and base course are placed on the construction site with crushed gravel, with average crushing value < 30 and abrasion loss < 40 at 500 revolutions, placed in <20 cm thick layers and compacted at 95% maximum dry density. After this, an asphalt prime coat is placed, followed by an asphalt base course and asphalt binder and wearing courses. An asphalt tack coat is placed before and after the binder course. These asphalt emulsion coats (prime and tack coats) are placed at the rate of 0.5 kg/m^2. This rate in UAE is lower than other regions—e.g., Giani et al. [51] used a 0.6 kg/m^2 rate in their pavement case study from Italy—but it is based upon the actual construction practice for this project, as obtained from the Abu Dhabi Municipality [52].

Maintenance of the road pavement section and other roadside components is a continuous process occurring periodically throughout the lifecycle of any road section. Biswas [4] proposed a minimum frequency of 25 years between asphalt course repaving. One study [6] replaced the asphalt base and wearing course after 30 years of construction without any earlier rehabilitation activities, while Vidal, Moliner, Martínez and Rubio [44] considered replacing 50% of the pavement section after 15 years. Overall, the frequency and extent of maintenance activities is dictated by previous experience and local conditions. Regarding recycled material usage in the M&R stages, Giustozzi et al. [53] used 85% recycled material for an Italian pavement rehabilitation, while Turk et al. [6] used cold in-place recycling for the sub-base and base courses of another European pavement section. Similarly, Biswas [4] used 100% recycled material for the sub-base course during rehabilitation stage.

Routine maintenance and periodic rehabilitation by milling and repaving the wearing course (<4.5 cm depth) every 5 years is analysed in this study based upon local guidelines [11], while the EOL stage is not modelled due to lack of data. The milled asphalt pavement from the highway section is assumed to be used as RAP during the M&R stage with over 80% replacement. Such practice (although novel in the case study region) is not a new idea in pavement research and real-world practices [54]. Some examples are Vidal, Moliner, Martínez and Rubio [44], Giani, Dotelli, Brandini and Zampori [51], and Harvey et al. [55] who used a similar method (in-plant/on-site recycling of top part of wearing course) in the M&R stage. From the performance perspective of WMA containing high RAP content, Jacobs et al. [56] found the stiffness, fatigue and deformation resistance to be similar to HMA mixes. Zhao et al. [57] found that high RAP WMA mixes had higher cracking resistance (16%) than HMA samples, similar moisture susceptibility and higher stripping resistance, regardless of pavement course and WMA technology. Nonetheless, future studies may conduct a series of detailed rutting, fatigue and cracking tests using the recommended recycled material mixes from this study to further explore performance-related sensitivity analysis, as the purpose of this study is to provide a comparative basis and precedence for LCA and sustainable road construction practices for the Middle East region, where such studies are minimal. The lifecycle inventory (LCI) used in this study for all alternatives described above is shown in Table 2. The material and equipment requirements for the HMA and WMA options were similar, except for the addition of synthetic zeolite. The LCI for synthetic zeolite for Abu Dhabi asphalt production is based on the data collected by Hasan, Whyte and Al Jassmi [26]. As mentioned earlier, the environmental impacts associated with RAP milling are not included, as it is assumed to be performed as part of the end-of-life operations of other previously constructed pavements in the region.

Table 2. Lifecycle inventory for the different pavement section alternatives considered in this study [1].

		Water	Sand	Local Silica Sand	Geotextile Fabric (Polypropylene)	20 MPa Concrete	Gravel	Clinker	Gypsum	Limestone
Earthworks backfill		454.6×10^3 L	19.8×10^3 m^3	13.10×10^3 m^3	93,650 m^2	650 m^3	9100 m^3	-	-	-
Concrete works (unit: tonnes)		22.03×10^3 L	2090.330	-	-	-	2280.153	416.053	21.897	23.050
Pavement courses varied between alternatives (material unit: tonnes)					**Crushed gravel**	**Sand**	**Virgin bitumen**		**Hydrated lime**	**RAP**
Baseline (virgin HMA) Warm-mix asphalt case	Granular sub-base course				448	-	-		-	-
	Unbound-base course				12,600	-	-		-	-
	4% bitumen asphalt-base course				6177	2901	384.3		144.1	-
	4% bitumen asphalt binder course				5719	2686	355.8		133.4	-
	4.5% bitumen asphalt wearing course				9242	4353	650.9		216.9	-
10% RAP wearing course	4.5% bitumen asphalt wearing course				8331	3920	585.8		183.7	1446
10% RAP asphalt base, 10% RAP binder course	4% bitumen asphalt-base course				5563	2613	345.9		122.9	960.7
	4% bitumen asphalt binder course				5149	2419	321.2		113.8	889.5
10% RAP asphalt base, binder and wearing	4% bitumen asphalt-base course				5563	2613	345.9		122.9	960.7
	4% bitumen asphalt binder course				5149	2419	321.2		113.8	889.5
	4.5% bitumen asphalt wearing course				8331	3920	585.8		183.7	1446
15% RAP wearing course	4.5% bitumen asphalt wearing course				7868	3703	552.5		173.6	2170
15% RAP asphalt base, 15% RAP binder course	4% bitumen asphalt-base course				5255	2469	326.6		116.3	1441
	4% bitumen asphalt binder course				4865	2286	302.4		107.6	1334
15% RAP asphalt base, binder and wearing	4% bitumen asphalt-base course				5255	2469	326.6		116.3	1441
	4% bitumen asphalt binder course				4865	2286	302.4		107.6	1334
	4.5% bitumen asphalt wearing course				7868	3703	552.5		173.6	2170
25% RAP asphalt base, 15% RAP binder and wearing	4% bitumen asphalt-base course				4640	2181	288.2		101.8	2402
	4% bitumen asphalt binder course				4865	2286	302.4		107.6	1334
	4.5% bitumen asphalt wearing course				7868	3703	552.5		173.6	2170

[1] *Material inventory is based on local data resources* [26] *and data collected from the contractor and client* [52] *for the case study project.*

3. Results and Discussion

Past LCA studies on pavement sections from other regions [44,58,59] have found significant improvement in the environmental performance with the usage of RAP content in the asphalt mixture. Our results for replacing virgin HMA with RAP and WMA for the analysed eight pavement section alternatives are presented in this section. The major sources of environmental burdens are from the material consumption, fuel consumed during operation of material extraction and construction, asphalt milling and equipment transport for both materials and equipment to the construction site and processing plant.

3.1. Distribution of Baseline Environmental Impacts across Pavement Cross-Section and Road Components

Prior to assessing the lifecycle environmental in/out-flows for any proposed RAP or other alternative-material-based road alternatives assessed against existing systems, the environmental footprint of the baseline case should be calculated to identify the shortcomings. Following the development of data inventory after information collection from local agencies, suppliers and contractors regarding the unit energy consumption and emission data for the materials required, the total energy consumption and emissions for the required quantity of materials in complete roadworks (pavement cross-section and roadside concrete works) were computed.

Figure 4 presents the LCA results for baseline case using virgin HMA across all lifecycle stages and road components. It can be deduced from Figure 4a that the majority of emissions were due to asphalt wearing course, followed by asphalt base course. Regarding asphalt wearing course, the environmental footprint share was highest for land use at 63,905.84 m^2a crop eq. (46%), ionising radiation at 36,950.31 kBq Co-60 eq. (44%) and energy consumption at 955,524.094 kg oil eq. (42%). For asphalt base course, the figures were: water consumption at 47,554.37 m^3 (29%), mineral resource scarcity at 1685.92 kg Cu eq. (28%), land use at 38,999.54 m^2a crop eq. (28%) and particulate matter emissions at 1014.97 kg $PM_{2.5}$ eq. (25%).

The environmental impacts of material transport had the highest share for the ozone-depletion-related parameters at 5.30–5.33 tonnes NO_x eq. (36–40%), followed by terrestrial ecotoxicity at 1.66 kilo-tonnes 1,4-DCB (27%), acidification at 2.25 tonnes SO_2 eq. (20%) and global warming potential at 0.6 kilo-tonnes CO_2 eq. (18%). The environmental footprint for the equipment transport constituted the lowest share, with notable impacts only observed for the terrestrial ecotoxicity at 4 tonnes 1,4-DCB (0.07%) and 1.73 tonnes CO_2 eq. (0.05%).

Table 3 compares the LCA results between the roadside concrete works and the pavement cross-section. Overall, it can be deduced that the environmental footprint of asphalt pavement sections is several times higher than the concrete works. It falls in the 82–98% range compared to the 2–18% range for concrete works. The highest impact for roadside concrete works was estimated for global warming potential, partially due to the production of cement [60]. This presents the need for a strategic response, targeting reduction in virgin asphalt demand for the studied road section, and results for this mitigation measure are explored in the next section.

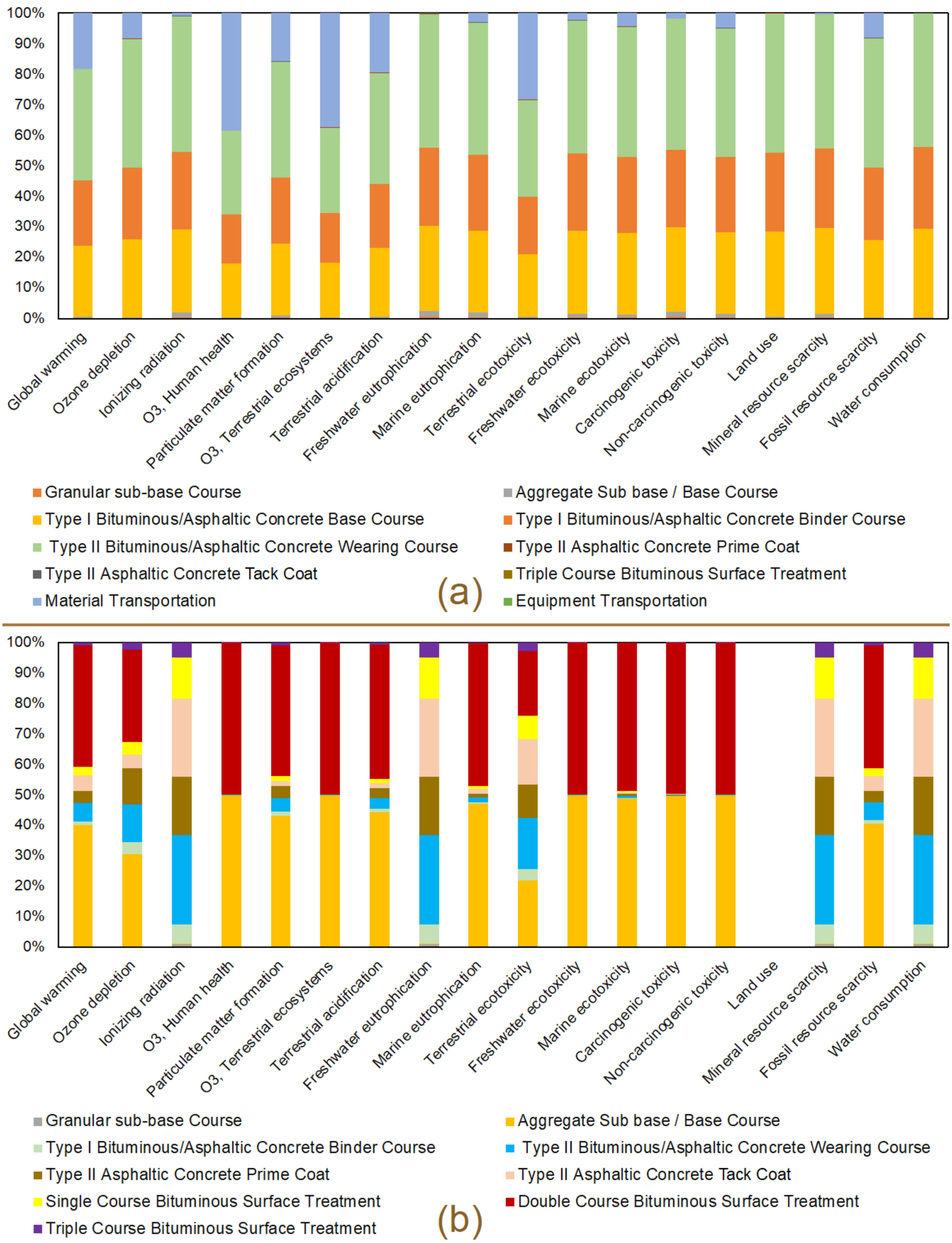

Figure 4. LCA results for the studied road in the baseline scenario using virgin materials for all lifecycle stages: (**a**) raw material extraction, processing, equipment and material transport to construction site, including M&R material; (**b**) construction and M&R.

Table 3. Comparison of LCA results between pavement cross-section and concrete works for the studied road in the baseline scenario.

Impact Category	Unit	Pavement Cross-Sections	Road Concrete Works
Global warming	kg CO_2 eq	4,228,255.96 (82%)	916,878.77 (18%)
Ozone depletion	kg CFC11 eq	2.25 (93%)	0.18 (7%)
Ionizing radiation	kBq Co-60 eq	166,016.81 (88%)	23,714.65 (12%)
O3, Human health	kg NO_x eq	16,996.54 (86%)	2764.63 (14%)
Particulate matter formation	kg $PM_{2.5}$ eq	8106.45 (91%)	825.90 (9%)
O_3, Terrestrial ecosystems	kg NO_x eq	17,537.81 (86%)	2798.68 (14%)
Terrestrial acidification	kg SO_2 eq	21,081.85 (91%)	2018.20 (9%)
Freshwater eutrophication	kg P eq	2444.88 (95%)	118.55 (5%)
Marine eutrophication	kg N eq	147.97 (88%)	20.55 (12%)
Terrestrial ecotoxicity	kg 1,4-DCB	49,446,163.7 (97%)	1,595,755.89 (3%)
Freshwater ecotoxicity	kg 1,4-DCB	403,686.81 (98%)	8842.74 (2%)
Marine ecotoxicity	kg 1,4-DCB	583,652.69 (98%)	12,841.3981 (2%)
Carcinogenic toxicity	kg 1,4-DCB	328,978.064 (95%)	17,490.87 (5%)
Non-carcinogenic toxicity	kg 1,4-DCB	14,000,051.7 (98%)	277,206.83 (2%)
Land use	m^2a crop eq	169,722.38 (91%)	17,721.06 (9%)
Mineral resource scarcity	kg Cu eq	47,753.86 (92%)	4362.81 (8%)
Fossil resource scarcity	kg oil eq	2,481,504.95 (94%)	152,165.38 (6%)
Water consumption	m^3	173,428.03 (92%)	14,168.98 (8%)

3.2. Pavement Alternative Material Options with 10% RAP Content

In alternative A1, 10% of the virgin asphalt in the asphalt mix for the wearing course was replaced by RAP, and the overall environmental impacts were slightly reduced. The most significant reduction was observed for energy consumption (FFD) with a 3.37 TJ (~3.24%) difference between the baseline case and the alternative material option with 10% RAP content. Land use impacts were also decreased from 169,722.38 m^2a crop eq. to 164,396.39 m^2a crop eq., corresponding to 3.14% reduction, as shown in Figure 5. On the other hand, when 10% RAP was added to the asphalt mixes for the asphalt base and binder courses instead of the wearing course in the second asphalt pavement recycling case (A2), a slightly higher energy reduction of 3.86 TJ (3.6%) was observed.

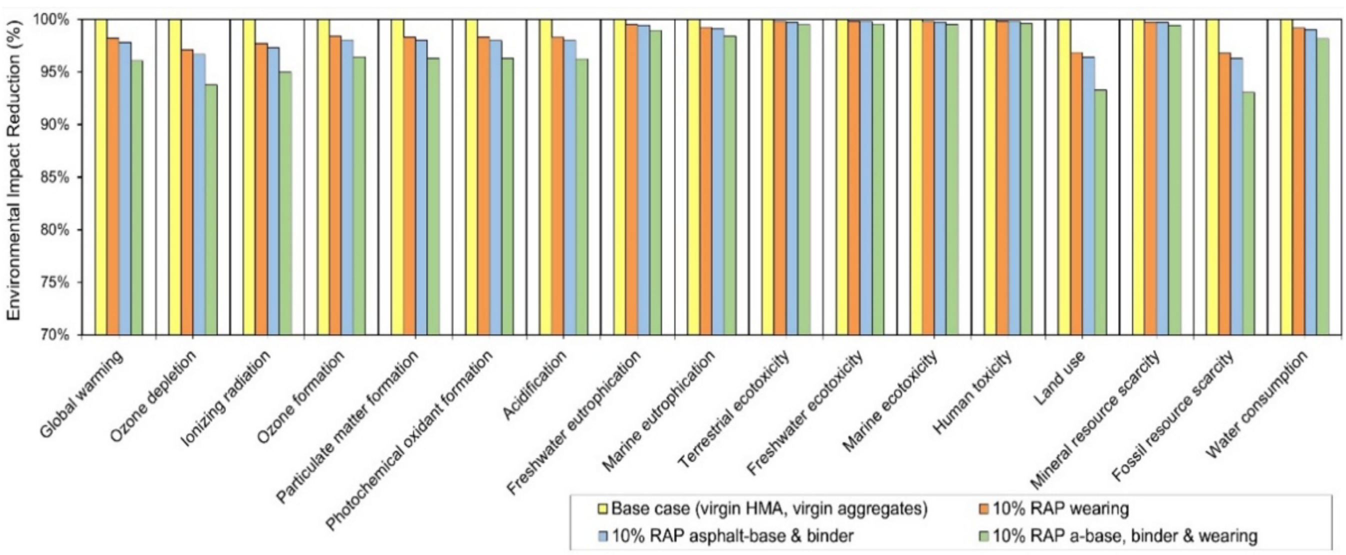

Figure 5. LCA results for the studied road using ≤10% RAP content in pavement courses vs. baseline.

Although, the third alternative (A3) resulted in the highest reduction across all analysed environmental footprint indicators, the results were not uniformly distributed. Furthermore, the reduction was more pronounced for land use, with 11,443.46 m^{2}a crop eq. (6%) reduction, energy consumption with 172.66 tonnes oil eq. (4.5%), ionizing radiation with 7953.43 kBq Co-60 eq (4%), ozone depletion with 0.14 kg CFC11 eq. (4%) and global warming potential with 0.17 kilo-tonnes CO_2 eq. (3%) reduction, as illustrated in Figure 5.

3.3. Pavement Alternative Material Options with 15% RAP Content

Figure 6 shows that among the recycled material options with 15% RAP content in the asphalt courses of the case study pavement section, the lowest environmental impact reduction was observed for the case using 15% RAP for only the wearing course. For this case, GWP decreased by 113.593 tonnes CO_2 eq. (2.69%), OD by 4.36%, land use by 4.71% and energy consumption by 4.86%. As previously noted, adding 15% RAP in the unbound aggregate base and binder layers with virgin asphalt mix for the wearing course showed slightly better performance in terms of environmental impact reduction.

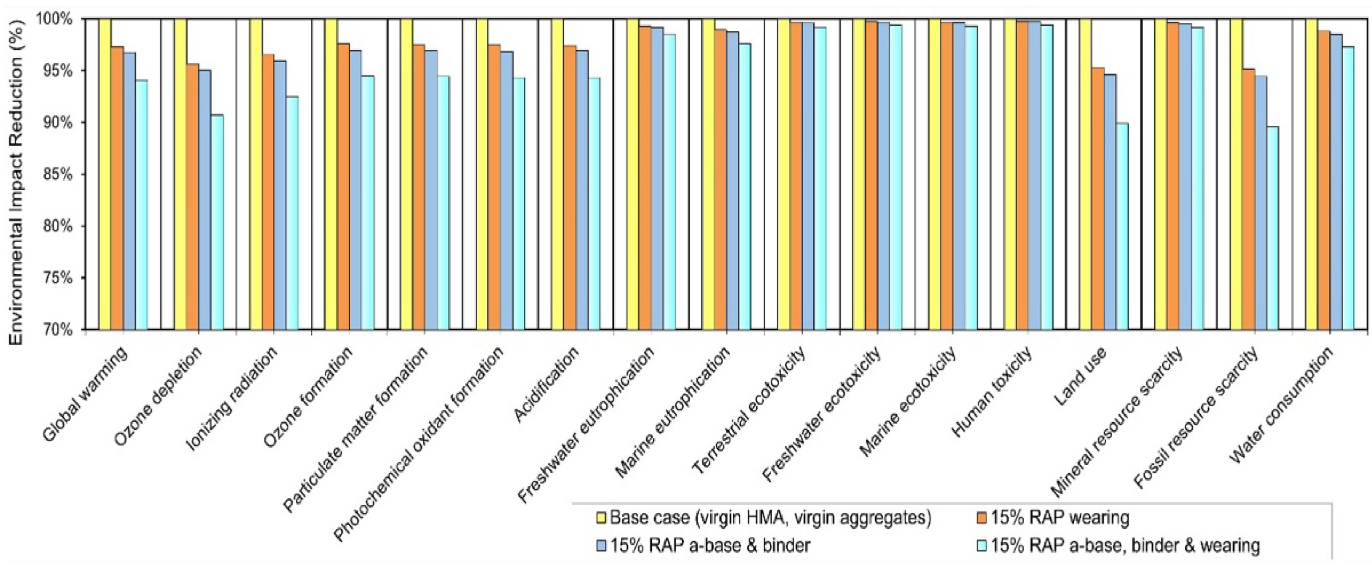

Figure 6. LCA results for the studied road using ≤15% RAP content in pavement courses vs. baseline.

As noted earlier, the highest environmental impact reduction in the 15% RAP cases compared to the baseline case was observed for the pavement constructed with 15% RAP content in the asphalt mixes for the wearing, binder and asphalt base courses. The results shown in Figure 6 show that land use again showed the highest reduction of approximately 10% with 17,165.19 m^{2}a crop eq. difference compared to baseline, energy consumption with 258.98 tonnes oil eq. (7%), and the lowest reduction was for non-carcinogenic toxicity with 76.594 tonnes 1,4-DCB (0.6%) difference than the baseline case.

3.4. 15% and 25% RAP Content Pavement Alternative Material Case and Virgin WMA Case

So far, the partial replacement of virgin HMA with RAP content across the different courses of the case study pavement cross-section resulted in environmental impact reduction across all estimated emission parameters. As discussed in the pavement LCA literature covered earlier, 25% or higher RAP addition as a substitute for virgin asphalt was found to provide reduction in environmental footprint without compromising on the pavement performance even in the wearing course [59], but due to a lack of adequate performance models for higher RAP-based HMA pavements in the UAE or the Middle East, an upper limit of 25% RAP only for the asphalt base course and 15% RAP for the binder and wearing courses was applied in this study during construction stage.

The results displayed in Figure 7 show that this RAP addition resulted in significant reduction in the environmental footprint from the pavement cross-section. Land use indicator showed a reduction of 20,341.81 m^{2}a crop eq. (11%), energy consumption at

306.8556 tonnes oil eq. (8%), ozone depletion at 0.25 kg CFC11 eq. (8%) and global warming potential at 0.30 kilo-tonnes CO_2 eq. (6%). These environmental impact savings are largely due to the environmental footprint of asphalt processing between the virgin asphalt pavement case and the 10% to 25% RAP case.

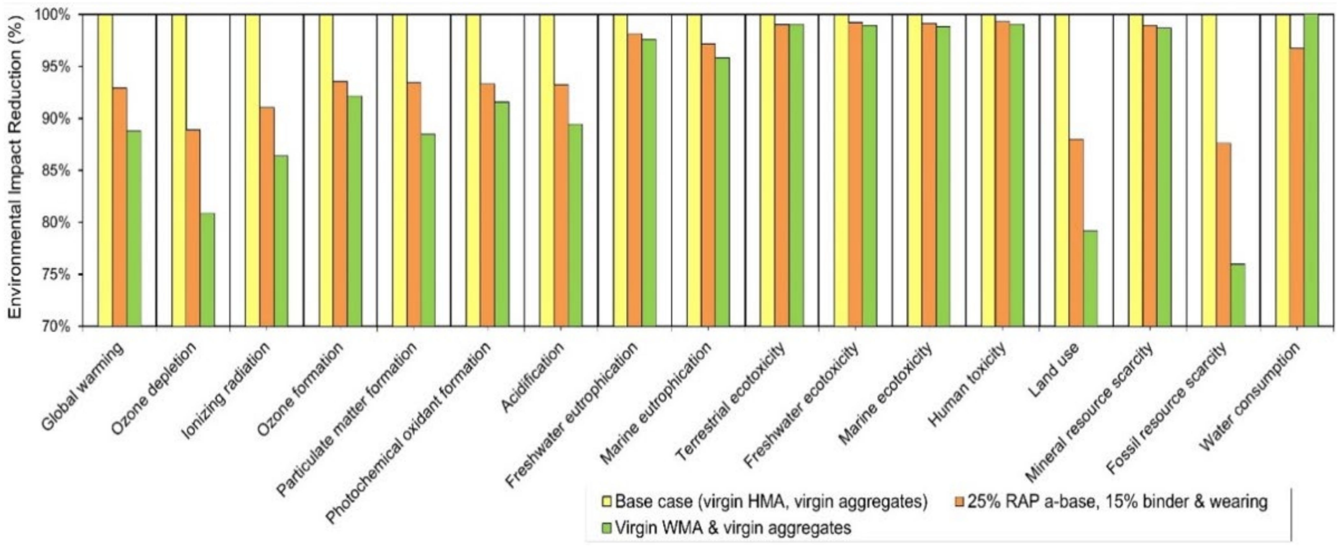

Figure 7. LCA results for the studied road using 10% ≤ 25% RAP content vs. baseline.

These reductions in the environmental impacts are comparatively higher than those reported in the literature (e.g., <5% reduction [4] and <6% reduction [51] after RAP usage in two recent studies) and highlight the need for the project-based lifecycle assessment for each road transport system project, as some pavements might contain thicker or multiple asphalt base courses across the cross-section due to the traffic and climatic conditions, which are not prevalent in the low-motorized-traffic roads analysed in the excessive European- and American-focused pavement studies.

As established in the LCI section earlier, the material transport, construction, maintenance, rehabilitation and end-of-life stages for both WMA and HMA pavements are similar. Since the impacts from the material extraction and processing stage formed the highest share of the overall environmental impacts, reducing the production temperature may be beneficial. The final scenario analysed a complete replacement of virgin HMA by virgin WMA to assess the benefit of this pavement designing approach. Roads in the UAE and the Middle East are largely constructed using HMA, with no WMA roads currently present. However, research and interest from the industry is now developing due to the comparative lower environmental impact and perceived costs [35].

For our studied highway section, we found that the WMA pavement alternative was significantly more successful in reducing the overall environmental footprint. Generally, the land use indicator showed a reduction of 35,373.98 m^2a crop eq. (19%), 595.86 tonnes for oil eq. (16%), ozone depletion at 0.43 kg CFC11 eq. (14%), ionizing radiation at 21,565.15 kBq Co-60 eq. (11%), particulate matter formation at 0.94 tonnes $PM_{2.5}$ eq. (8%) and global warming potential at 0.48 kilo-tonnes CO_2 eq. (6%). These results presented in Figure 7 confirm the findings from the literature that the environmental impact of WMA is considerably lower than HMA pavements. It can be stated based on these estimates that the lowered temperature due to usage of WMA compared to HMA in constructing and performing M&R of the studied pavement is more important than just partially using RAP as a virgin material substitute.

Although our WMA mixture used synthetic zeolite to achieve this lowering in temperature without compromising on strength and durability performance, it had little to no impact on the emissions, as the overall environmental footprint remained lower than the baseline case and even the 10–25% RAP content case. Only the water consumption indicator showed a higher value for virgin WMA pavement of 1440.77 m^3 (2%) compared to the higher RAP-based option. Nonetheless, the findings from this study recommend that the WMA pavements (or a combination of RAP and WMA pavement asphalt mixtures) will be a more environmentally effective option for the studied region or any other similar road project where thick asphalt-base layers are placed under binder and wearing courses.

4. Discussion on Critical Impacts

This study applied lifecycle methodology to calculate the environmental impacts of a 3.5 km-long dual carriageway case study in Abu Dhabi across pavement courses, concrete traffic barriers, concrete kerbs and parapets, and concrete foundation works for traffic signals and lighting with a 30-year service life from 2015 to 2045. A comprehensive analysis of environmental impact reduction was performed using recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and slag as alternate material and production options. Actual field data for the road section using virgin materials and traditional asphalt production mix for pavement works and Portland cement concrete for the complete concrete works were used as the baseline case.

Although environmental impact reductions across all the 18 analysed indicators in the ReCiPe method were noted over the asset's lifecycle, as covered in previous sections, the most critical impact reductions were calculated for 8 indicators. The highest of these was land use, which had 19% reduction for WMA option and 11% reduction for RAP (25% RAP in asphalt base and 15% RAP in binder and wearing courses and also using RCW). This is largely due to the demand for plant infrastructure being lower, which minimised the agricultural land damage and landfill demand. For RAP-based option with RCW, this was due to the lower need for asphalt and usage of recycled construction waste instead of virgin aggregates; operations for crushed gravel require a dedicated infrastructure compared to crushing and screening RCW [36,61].

The second highest reduction was observed for the fossil fuel consumption indicator, which is an indicator of the energy demand for pavement construction and maintenance. For WMA, this is caused by less need for producing and laying the asphalt mix, as the temperature for producing HMA is at least 140 °C, while WMA can be produced at 100–140 °C [35]. Similarly, the utilisation of RAP instead of virgin asphalt in the RAP-based option with RCW significantly decreased the demand for virgin asphalt, thereby reducing energy need for asphalt production. Next, ozone depletion (14% for WMA and 9% for RAP containing RCW) and ionising radiation (11% for WMA and 8% for RAP containing RCW) were significantly reduced. The production and construction of pavement layers lead to a release of harmful compounds that deplete the protective ozone layer and increase global radiation [55], and a reduction in material demand due to WMA and RAP (containing RCW) usage decreased the release of these chemicals in our case study analysis. It should be noted that these lower material demands were also responsible for the reductions noted in particulate matter (8% for WMA and 5% for RAP containing RCW) and acidification (7% for WMA and 5% for RAP containing RCW), which are both changes in global impacts caused by modifying the local site emissions.

The reduction in global warming potential (GWP), an indicator of the GHG emissions towards achieving the net-zero-carbon road construction and maintenance, was also noted. For the RAP-based option that also utilised RCW across the pavement layers instead of virgin asphalt and aggregates, the GWP value reduced by 6%. This can be due to the significantly lower per unit emission rate when using recycled asphalt instead of the high bitumen usage demand for producing virgin asphalt. Additionally, recycled aggregates carry a much lower carbon emission load compared to virgin aggregates while containing comparable strength and durability characteristics in ground structures [51,62,63]. However, the majority of carbon impact reductions were due to the lower asphalt consumption. This observation is further supported by the higher reduction in GWP noted for the WMA option, which estimated a decrease of approximately 8%. It is noteworthy that the savings in energy consumption are more than double those of the savings in GWP emissions, which creates an interesting incentive to promote the usage of WMA in the studied region, which has a high demand for HMA in constructing flexible pavements.

The lowest reduction was noted for ecotoxicity indicators, followed by water consumption. Water conservation is an important issue in the region, as the per capita domestic water use in UAE is approximately 353 L/day, around 41.2% higher than the global average due to rapid industrialisation, urbanisation and construction boom in the region. However, the current water demand is largely met by desalination (42%) and wastewater recycling (14%). Additionally, natural gas consumption in desalination and wastewater recycling plants [64], as well as sustainable management of existing water resources, are the larger issues behind the regional water-related impacts. In relation to reducing the water use and water pollution in the case study region, these water resource management processes and other local water supply grid issues need to be studied in depth and are beyond the scope of this research work.

5. Conclusions

Due to the fragmented nature of existing research on LCA of roadworks, the environmental benefits of recycled material use in different components of roadworks, including earthworks, pavement courses and concrete works, have thus far not been compared for the same functional unit. Thus, this study contributes by establishing a detailed inventory for all involved stages, sub-stages and components of the pavement construction process, which may be used as a sample for future studies, specially targeted at conveying the results to the government agency decision makers, particularly in regions where virgin material usage is dominant and LCA studies on the environmental impact reduction in alternative pavement material technologies are considerably less numerous.

The assessment results obtained from this study analysed a baseline case, which was based on the actual on-site project works. The virgin materials used in different pavement courses were replaced, and variations in energy consumption and air emissions were plotted. Similarly, WMA was used to replace HMA in asphalt layers. Since this study is site specific and based on a real-world case study from Abu Dhabi, actual field data were collected from the Abu Dhabi Municipality to analyse the complete burden of all items tendered and constructed as part of pavement works to promote sustainable alternatives. The lifecycle inventory data were thus procured from the project client and contractors for the case study roadworks. LCA was performed in SimaPro using ReCiPe midpoint H method, which was used to calculate the emissions and energy consumption. The energy and material consumption values for producing each raw material were modified from the default values in the Ecoinvent database based upon the actual production process inputs from the local suppliers. Material and equipment transport vehicles data were first obtained from project specifications, and Ecoinvent data inputs for suitable vehicles were then modified.

The study results showed that the environmental impacts from road construction in the case study region were significantly decreased by recycled material usage and reduction in production temperature. Raw material extraction and processing stage was the largest contributor to the environmental impacts over the 30-year lifecycle. The most significant differences between impacts were noticed in land use, energy consumption, ozone depletion, ionizing radiation, particulate matter formation and global warming potential at 19%, 16%, 14%, 11%, 8% and 6%. The environmental impacts of other impact categories, except water consumption, remained largely unchanged for the eight alternative cases assessed in this study. Overall, the temperature-lowering benefit of WMA compared to HMA proved to be more effective, yet partial replacement of virgin HMA with RAP during construction stage may still prove to be quite effective as an interim solution while such technologies are being developed in the developing world. It should be noted that this study was conducted as a streamlined lifecycle assessment and not a considered cost analysis, which is often covered in separate lifecycle cost analysis (LCCA). However, the actual implementation of these sustainable solutions for roadworks is highly dependent upon the cost parameter, which was not analysed in this study. A follow-up study by the authors shall analyse cost performances of different sustainable alternatives against the baseline for initial cost, routine maintenance, major rehabilitation and other cost indicators.

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