Life cycle assessment of roadworks in United Arab Emirates: recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach

Author names and affiliations:

Umair Hasan[a,c*], Andrew Whyte[a], Hamad Al Jassmi[b,c]

[a] School of Civil and Mechanical Engineering, Curtin University, Perth, WA 6845, Australia.

[b] Department of Civil and Environmental Engineering, United Arab Emirates University, Al Ain, UAE.

[c] Roadway, Transportation and Traffic Safety Research Centre, United Arab Emirates University, Al Ain, UAE.

[*] Corresponding author. Email: umair.hasan@postgrad.curtin.edu.au.

Highlights:

- A comprehensive life cycle assessment for a UAE highway section by ReCiPe method.
- Employment of construction waste, RAP, warm-mix and GGBFS to reduce impacts.
- Earthworks and concrete works had a significant environmental burden in roadworks.
- Recycling and industrial by-products reduced impacts for concrete and earthworks.
- For asphalt courses, environmental benefits achieved by coupling warm-mix with RAP.

Abstract

Life cycle assessment methodology was applied in this study to calculate environmental impacts of a 3.5-km-long dual carriageway asphalt highway section case study in Abu Dhabi across following life cycle stages: material extraction and production, material and equipment transport, construction, maintenance and rehabilitation; assuming a 30 years lifetime. Environmental impact assessment for air emissions and energy consumption generated by complete roadworks, namely: earthworks; pavement courses; concrete works for traffic barriers, kerbs, parapets, traffic signs, and light systems. A comprehensive analysis of environmental impact reduction was performed using recycled construction waste; reclaimed asphalt pavement; warm-mix asphalt with synthetic zeolite additives; 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. Routine maintenance and periodic rehabilitation by milling and repaving wearing course (<4.5cm depth) every 5 years was also analysed from an environmental impact reduction perspective. Environmental assessment considered all indicators from ReCiPe midpoint method. Results show that earthworks account for a significant portion (26% of CO_2eq.) of the environmental impacts for complete roadworks. The life cycle impact results of hot-mix asphalt and warm-mix asphalt were almost equal due to addition of synthetic zeolites. Results showed significant environmental impact reduction across all indicators, after coupling all alternate options as: 34% in CO_2eq.; 48% in energy consumption; 24.4% in NO_xeq.; 21.53% in $PM_{2.5}$eq.; 21.2% in acidification; and, 10.4% in land use. Monte Carlo simulations confirm these results and the sensitivity of environmental benefits to the allocation methodology was also investigated, which showed that the results were only marginally sensitive to the allocation approach. This study noted higher environmental benefits than reported in roadworks literature due to alternate material and asphalt production options.

Keywords: road sustainability; asphalt pavements; life cycle assessment; recycled materials; warm-mix asphalt; pollutants.

1. Introduction

Construction, operation, and maintenance of roads carry a significant environmental impact (Anastasiou et al., 2015). Roadworks account for around 28% of global energy consumption and approximately 22% of global CO_2 emissions (Abergel et al., 2017). According to 2014 estimates, road transport sector in the Emirate of Abu Dhabi in the United Arab Emirates generated more than 12 million tonnes CO_2eq. emissions, accounting for approximately 63% of the total transportation sector-related GHG emissions (Hill et al., 2012; SCAD, 2014). Abu Dhabi Transport Master Plan 2009 acknowledges that the UAE has one of the largest per capita emissions globally, i.e., 23.3 tonnes per

capita of CO_2 emissions (DoT Abu Dhabi, 2009; Bank, 2019) and needs a low carbon road transport network (Hasan et al., 2019a, 2020).

The majority of the 21,673 km paved road in Abu Dhabi is asphalt constructed from virgin materials. Abu Dhabi City Municipality (2010) manual addresses the use of reclaimed asphalt pavements, in-situ recycling and stabilisation techniques to reduce the environmental impacts. However, there is a considerable lack of research empirically plotting the environmental benefits of using such materials on actual pavement projects from the UAE and the Middle East region overall. Alzard et al. (2019) have explored the CO_2 emissions produced by road projects in Abu Dhabi, but the study was limited in scope.

Life cycle assessment (LCA) is used to analyse the impact of infrastructure development on the environment (ISO 14040, 2006). Researchers have attempted to address various stages involved in the cradle-to-grave/cradle life cycle of infrastructure (Batouli et al., 2017; Moretti et al., 2018), yet, construction equipment transport is not modelled in the existing literature. Blengini and Garbarino (2010) explored the environmental benefits of screened and crushed recycled construction and demolition waste (RCW) in Italy. They found that RCW used for road base/sub-base construction corresponds to around 14 kg/tonne of avoided GHG emissions. However, regional constraints like transport distance (Turk et al., 2016) may also have some influence on the environmental benefits from extraction and haulage of recycled materials compared to virgin materials and the LCA results between studies in different regions may vary.

Reclaimed asphalt pavement (RAP) obtained after milling and screening existing asphalt pavements is also proposed as a viable alternative to mitigate the high GHG burdens of bitumen and aggregates by various researchers (Praticò et al., 2015; Guo et al., 2018) and transport agencies (AASHTO, 2012). Miliutenko et al. (2013) have shown that HMA mixes with RAP content have same technical characteristics (stiffness, fatigue and deformation resistance) as virgin HMA. Giani et al. (2015) explored the replacement of virgin asphalt by 10% RAP in hot-mix asphalt (HMA) surface course and by 20% RAP in HMA binder course of a 1 km asphalt pavement section in Italy. They found that HMA RAP alternative exhibited 688 tonnes CO_2eq. (6.8%) GHG emissions reductions.

Warm-mix asphalt (WMA) is another emission and energy impact reduction strategy used by producing asphalt mixtures at lower temperatures (100°C–140°C) compared to hot-mix asphalt temperature range of 138°C–160°C (Tarefder and Pan, 2014). This reduction in WMA production temperature is traditionally achieved by addition of asphalt additives, such as water-based foaming agents (zeolites), chemical additives (polymers) and organic additives (waxes) which may affect the life cycle environmental impacts (Butt et al., 2014; Butt and Birgisson, 2016). Regarding performance, Zhao et al. (2012) found that the fatigue resistance, moisture susceptibility and rutting resistance of WMA containing high percentages of RAP was significantly higher than HMA samples. Almeida-Costa

and Benta (2016) noted that due to the lower energy requirements for heating aggregates, the total energy consumption reduced by 0.041 GJ (~18.46%) between the production of HMA and WMA.

AzariJafari et al. (2016) note that since site clearance and earthworks and involve large volumes of material, future pavement LCA studies should include analysis on environmental benefit of recycled alternatives for this component. Additionally, the environmental burden of concrete for kerbs, traffic barriers and parapet walls along the road are usually unacknowledged in pavement LCAs. Concrete is also used for foundation works of traffic signs and streetlight systems, however, it is not studied in the context of the complete pavement life cycle results. Yang et al. (2015) and Kim et al. (2016) propose that for concrete mix with ground granulated blast furnace slag (GGBFS) replacement in the range of 15%–80%, significant reduction in environmental impacts occur corresponding to insignificant strength loss compared to ordinary Portland cement (OPC) concrete for the 20MPa–170MPa range.

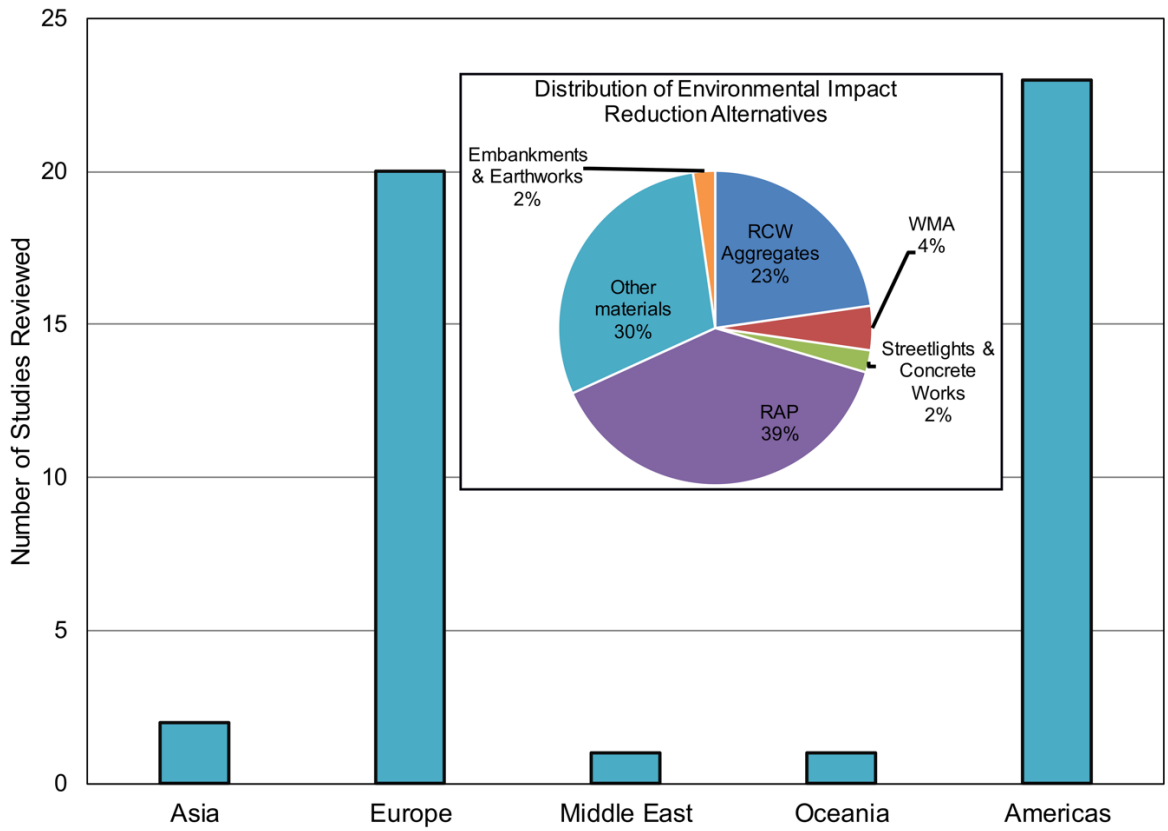


Figure 1 Regional and alternative distribution of LCA studies on pavement sections and other roadworks in recent literature

Regional conditions, e.g., transport infrastructure (Hoque et al., 2019a, b) and material recycling/extraction plants, construction machinery and techniques used, road design and cross-sectional characteristics and local material supply chain may also influence the direct interpretation of results (Yi et al., 2007; Anastasiou et al., 2015). Figure 1 covers the three most recent state-of-the-art reviews (AzariJafari et al., 2016; Balaguera et al., 2018; Hasan et al., 2019b) on the LCAs of pavement

sections and associated roadworks. The detailed list and number of references from each review study is provided in the appendix (Table A.1). The majority of research was conducted on RAP and RCW usage as environmental impact reducing alternatives for pavement sections in Europe and the Americas.

In the current study, a comprehensive analysis of environmental benefits of RCW as an alternate for natural aggregates, RAP against virgin asphalt and WMA (with synthetic zeolite additives) against HMA is performed. Different combinations of recycled material alternatives across the pavement cross-section are analysed over 30-year life cycle to calculate the environmental advantages of each alternate option. Additionally, LCA of GGBFS as an alternate option in concrete works is also performed. This comparative environmental benefit assessment for complete roadside works is not only a relatively new and concise study in pavement literature, but it is also the first such study performed in the context of UAE and the Middle East region using different environmental indicators.

2. Methodology

This study uses LCA methodology to calculate and analyse the environmental impacts for roadworks over the life cycle of a highway project in Abu Dhabi city. The life cycle stages considered are further explained in Section 2.2 below. LCA is performed according to the ISO 14040 (2006) guidelines in the following phases: *goal and scope* definition, quantifying and developing *life cycle inventory* (LCI) and *life cycle impact assessment* (LCIA) and *interpretation* in terms of results and discussion. The life cycle assessment software package SimaPro 8.5.2 was used to perform the study (Vidal et al., 2013; PRé Consultants, 2016). ReCiPe (Goedkoop et al., 2009) is the only analysis method available in SimaPro for global LCA studies and is used in this study. Case study data is an extension work on the Sheikh Zayed Bin Sultan Street, originally completed in 2009 by adding one lane (3.65m width) and a shoulder (3m width) each side on the 3.5-km dual carriageway asphalt highway section. Missing data, e.g., UAE electricity mix and transport vehicles were developed based on appropriate resources from existing literature and Ecoinvent v3.3 database.

2.1. Goal and scope

The goal of the current study is to calculate and compare the environmental emissions and energy consumption between different recycled (RCW and RAP) and producing temperature (WMA vs. HMA) pavement construction alternate options and industrial by-products (GGBFS) as partial replacement of Portland cement for associated roadside works. In this way, the environmental impact reduction performance of different options for complete tender works for constructing an asphalt road can be compared across the roadworks components and the best performing alternative can be identified for real-world applications. The functional unit for the LCA methodology used in this study is defined as a 3.5-km dual carriageway highway section with two lanes (3.65m + 3m width) in each direction. The two carriageways are separated by concrete barriers. Concrete kerbs are constructed on each side of the

carriageways. The pavement cross-section considered in this study is illustrated in Figure 2. The average lifetime of asphalt roads varies in the literature, e.g., 100 years (Biswas, 2014), 50 years (Santos et al., 2015) and 30 years (Giani et al., 2015; Turk et al., 2016). This study assumed service life of 30 years based on local government agency guidelines (DoT Abu Dhabi, 2009).

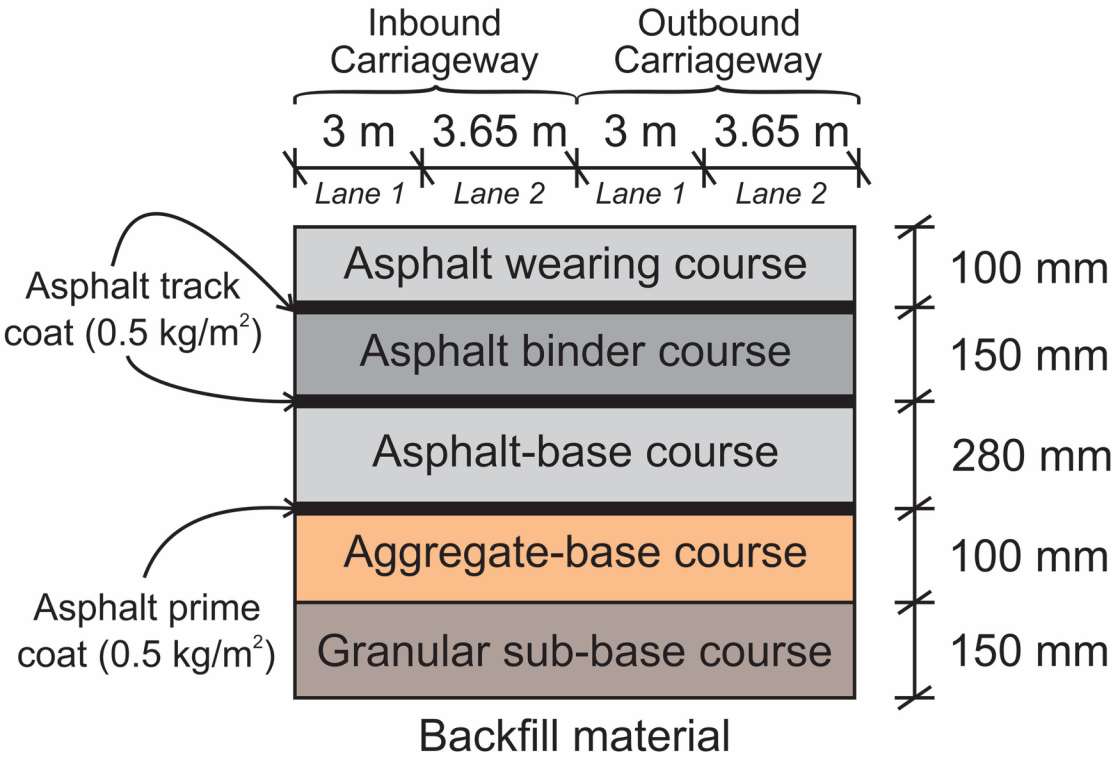


Figure 2 Case study pavement cross-section

2.2. Description of alternatives and system boundaries

The following life cycle stages of roadworks are considered in this streamlined LCA: raw material extraction, material production/processing, material and equipment transport, construction, maintenance and rehabilitation (M&R) and periodic recycling of the pavement wearing course. This study is performed as a streamlined LCA. The operation and usage stage and end-of-life disposal/landfilling are not considered in this study due to lack of precedence to establish the emissions associated with these stages in the case study region. A proportion of asphalt from wearing course is milled up to the depth of 4.5cm every 5-year as currently practiced in the field (ADM, 1997) during M&R stage.

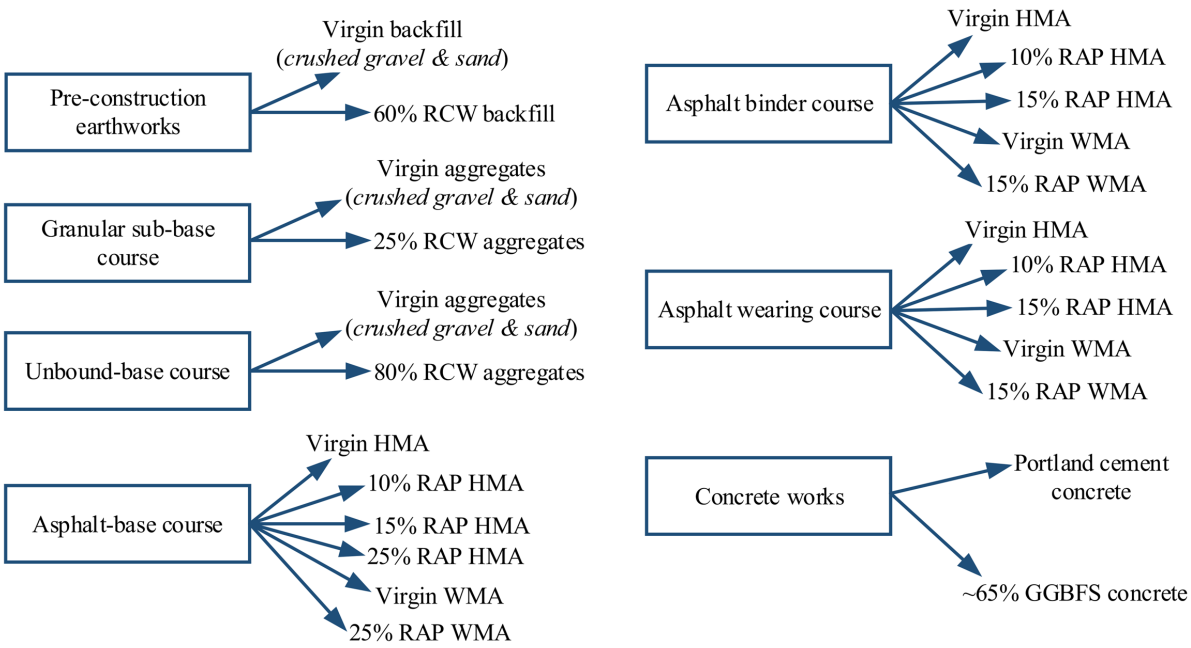


Figure 3 Environmental impact reduction alternatives for each component of case study roadworks

The milled asphalt is then transported to an asphalt plant and mixed with virgin bitumen for repaving the wearing course. It is assumed to be a continuous process after the end of the initial 30 years lifetime. Processes post-30 years are not modelled due to unavailability of data on pavement conditions, traffic pattern and historical pavement reuse records. The environmental burdens of RAP milling (in M&R stage), transport and processing are included. However, similar to pavement LCA methodology in literature, the burdens from RAP milling during initial construction process (when it is used as an alternate material) are not included (Harvey et al., 2016). The material transport of this recycled RAP from recycling facilities (for screening and storage of RAP) to the asphalt plant is included in the analysis. Elchalakani et al. (2014) in an Abu Dhabi region-based study recommend 80% OPC replacement by GGBFS for maintaining optimum durability while reducing the environmental impacts (~107 kg/m of CO_2 emissions). The current study uses a conservative replacement of OPC (~65%) by GGBFS in the concrete used for the case study roadworks. The different environmental impact reduction alternatives (Figure 3) and life cycle stages in the system boundaries (Figure 4) are described below.

a) ***Material extraction, production, and processing*** include extraction and plant processing of asphalt, aggregates, cement, and admixtures, etc. required for pavement construction and roadside works. The Abu Dhabi Municipality Road Specifications Manual (ADM, 1997) specifies that crushed gravel with sand should be used as backfill in pavement construction. Local fine silica sand or *sweet sand* from red dunes in Abu Dhabi is also used as non-load bearing backfill material.

Crushed natural gravel carries a significant environmental impact due to mining, transport and production operations. The current study assesses locally-sourced RCW as an alternative material for crushed natural aggregate in backfill, sub-base and unbound granular aggregate-base (u-base) construction. Abdelfatah and Tabsh (2011) reviewed the use of locally-sourced RCW in the UAE and other Gulf Cooperation Council countries. They note that pavements constructed with RCW sub-base/base courses exhibited higher resistance to deflection than natural gravel courses, in laboratory performance tests. Similar performance results were noted by (Hasan et al., 2016a, b). Asphalt production and mixing is a major source of environmental impacts due to fuel consumption, machinery, and supply-chain infrastructure. RAP and WMA are also assessed in this study against virgin HMA to reduce the energy-related emissions. Industrial by-product *GGBFS is also used as a partial replacement of Portland cement* for constructing concrete barriers and kerbs and foundations of traffic lighting and markings.

b) ***Material transportation to the construction site*** is an important stage in roadworks life cycle and as such, data from the local suppliers needs to be collected as environmental impacts depend upon the distance to material production plants and vehicles used for by-road material transportation to the site. Heavy goods vehicles (HGVs) fuel consumption is the main source of emissions in this stage.

c) ***On-site equipment transportation to the construction site*** is also significant for the actual construction process to commence and mostly HGVs are used to transport excavators, milling machines and other roadworks equipment. Similar to the material transport by roads, data from local resources are used to model equipment transport.

d) ***Construction*** environmental impacts are due to the operation of on-site equipment like excavators, asphalt pavers, compactors, and wheel-loaders, etc. Constructing traffic and carriageway concrete barriers, kerbs, concrete foundations for traffic lights and road markings also constitute a part of the total environmental burdens during road construction. This study considers environmental impacts from all of these road construction processes. The environmental impacts from the vehicles on the work-zone (due to traffic delays in construction and M&R stages) have not been considered in this streamlined LCA as this study focuses on alternate material use for pavements and these impacts are considered to be the same for all alternatives due to the same construction actual on-site activities.

e) ***Road use*** environmental impacts are primarily due to emissions from fuel consumption of the vehicles using the road surface characteristics and vehicle-pavement interactions. The surface structure, roughness and other characteristics affect the rolling resistance from pavements to the vehicles which affects the fuel consumption of vehicles. Microscopic vehicle simulation models can measure per-second driving resistance and acceleration-deceleration profile of each vehicle using any case study road. However, Wang (2013) note that microscopic emissions model such as Comprehensive Modal Emission Model, rely on time consuming data input and also neglect the pavement information.

Although, other models, e.g., MOVES developed by the United States Environmental Protection Agency can be modified to address dynamic vehicle speeds and rolling resistance induced by pavement surface (Abou-Senna et al., 2013; Wang, 2013), such models rely on data from North America and European regions and may not be applicable to the Abu Dhabi carriageway studied here. Thus, road use stage is considered outside the system boundary of this study as a separate follow-up study by the authors is currently underway to calculate traffic flow emissions addressing these issues.

e) ***Routine maintenance and rehabilitation*** environmental burdens are from routine maintenance of the road section during its life cycle, frequent rehabilitation activities after a specific time period (considered to be repaving of top 4.5 cm of wearing course every five years in this study based on current practice in the case study area) after milling the worn-out wearing course which has reached its end-of-life. This generates another opportunity to reduce environmental impacts. To reduce impacts from this stage, this study compares environmental impact reduction between using virgin HMA materials and 85% of RAP content (obtained after pavement milling in the M&R stage) mixed with virgin asphalt through warm-mix production process in an asphalt plant. As stated earlier, Zhao et al. (2012) have shown that the performance of WMA pavement containing high proportion of RAP content is equal or higher than the virgin HMA samples. Additionally, Biswas (2014) have reviewed studies on 80-100% RAP use in the M&R stage with adequate pavement performance results. Nonetheless, the current study is aimed to establish precedence for LCA studies in the case study region, where LCA studies on recycled material usage for pavement construction are minimal. A future study may perform sensitivity analysis on the structural performance of pavements containing recycled materials after fatigue cracking, permanent deformation and dynamic moduli laboratory tests have been performed. Similar to the initial construction stage, GGBFS is used as an alternate option to Portland cement for routine maintenance of concrete roadworks. This study does not consider landfilling/disposal after end-of-life stage as there is no precedence to establish the associated emissions in the region based on consultations with the local experts in the UAE.

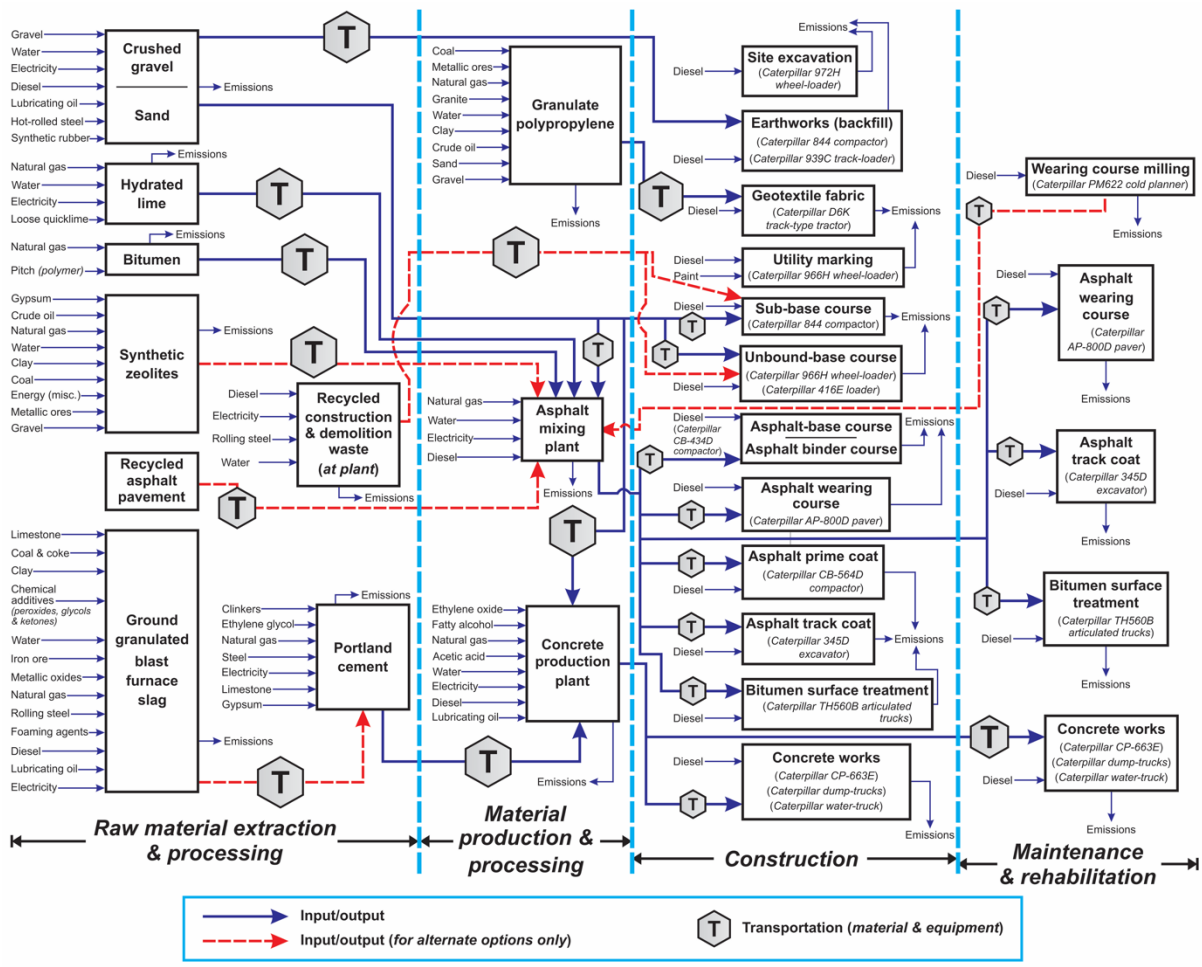


Figure 4 System boundaries of the life cycle stages and processes (*including allocation assumptions*)

In case of LCA studies on roadworks, the reuse of pavement materials (such as RAP) and alternate cementitious materials (such as GGBFS and fly ash, etc.), possess a challenge related to the allocation of environmental benefits and impacts. This issue is related to the partitioning of inputs and outputs between products and sub-products of any process, specifically as to how much of the burden should be assigned to product (e.g., steel) and co-product (e.g., GGBFS). Similarly, how much of the benefit of RAP recycling should be assigned to the original/old pavement producing the RAP content and the current/new pavement using recycled RAP to replace some of its binder content as a recycled alternate option. Reporting the allocation assumptions is more significant in the case of open-loop recycling (i.e., by-product or waste from one system is used in a completely different system, e.g., recycled RAP used in asphalt courses originating from a different pavement, and, RCW from buildings and other concrete structures used in sub-base/base courses) normally conducted for pavements.

The ISO 14044 (2006) guidelines generally recommend avoiding allocation by either expanding system boundary or dividing the process into subprocesses based on the physical (mass, energy, volume) or economic relationships between the different (co-) products. The cut-off or 100:0 approach

is normally applied in existing research on pavements (Giani et al., 2015; Harvey et al., 2016), where the benefits of using recycled materials or industrial co-products (e.g., GGBFS) are not transferred upstream and are instead credited downstream (i.e., to the new pavement using the recycled materials). Following the ISO guidelines (Lee and Inaba, 2004) and existing LCA practices related to roadworks and pavements (Harvey et al., 2016), this study allocates all burdens associated with the recycling and reuse of RCW and RAP to the case study pavement (i.e., the pavement utilising recycled materials), while the burdens associated with the production of RCW and RAP are not included. The environmental burdens associated with processing and transport of RCW to the construction site are included. Similarly, the environmental impacts associated with the transport and processing of RAP (from open-loop recycling, i.e., RAP from other older pavements and used as recycled material for the case study pavement) to the asphalt plant are included. GGBFS is treated as a co-product from the steel production industry and the relevant environmental burdens associated with the production and processing of GGBFS are included as per Harvey et al. (2016). The allocation assumptions are shown in Figure 4.

3. Life cycle inventory (LCI) – Abu Dhabi case study

3.1. Material extraction, production, and processing:

The actual field data regarding the backfill on the case study site (as per local municipality guidelines) is used as baseline case (*virgin backfill*). Based on the existing literature (Rathje et al., 2002; Blankenagel, 2005; Hasan, 2015; Vieira and Pereira, 2015), RCW is used as partial replacement of virgin aggregates in backfill (*60% RCW backfill*). This study also used RCW as the recycled (25% RCW) *sub-base* and (80% RCW) *u-base*. Sand, crushed gravel and bitumen are used in asphalt plants with hydrated lime as filler to increase asphalt stiffness and rutting resistance (Vidal et al., 2013). As per the Abu Dhabi municipality guidelines (ADM, 1997) and actual field data; HMA with 4% bitumen as binder, 30.2% sand as fine aggregates, 1.5% hydrated lime as filler and 64.3% crushed gravel as coarse aggregates mixed in a batch mixer plant is used for asphalt base course and binder course. The wearing course asphalt uses 4.5% bitumen, 30.1% sand, 1.5% hydrated lime filler and 63.9% crushed gravel as coarse aggregate.

RAP is a traditional alternative material to reduce the bitumen and aggregate content in asphalt. Current Abu Dhabi guidelines mention 15% RAP usage in binder course (Department of Transport Abu Dhabi, 2018). However, researchers investigated different percentages of RAP replacement in pavement construction. Ventura et al. (2008) used up to 30% replacement in binder course. Giani et al. (2015) applied up to 30% RAP in base course, 20% RAP in binder course and 10% RAP in wearing course. Due to the high strength of asphalt base (Rys et al., 2017) and findings by Zhao et al. (2013) on strength performance of high RAP concrete in asphalt pavements, this study explores the environmental benefit of up to 25% RAP usage in asphalt base course. However, due to limited RAP experimental

studies in Abu Dhabi and the Middle East region, an upper limit of 15% RAP in wearing and binder courses is used.

Table 1 LCI of the production of asphalt mixes

Input/Output	Hot-mix asphalt (HMA)	Warm-mix asphalt (WMA)
Natural Gas (*MJ/tonne*)	300	240
Electricity (*kWh/tonne*)	6	6
Diesel (*MJ/tonne*)	8.49	8.49
Water (m^3/*tonne*)	0.01003	0.01003
Emissions to air		
CO (*kg/tonne*)	0.16	0.133
CO_2 (*kg/tonne*)	16.8	15.1
NO_x (*kg/tonne*)	0.0125	0.0102
PAH (*kg/tonne*)	3×10^{-6}	1.96×10^{-6}
NMVOC (*kg/tonne*)	0.00441	0.003402
SO_2 (*kg/tonne*)	0.0023	0.00187
$PM_{2.5}$ (*kg/tonne*)	0.00415	0.00338

The same upper limits are considered for WMA as Zhao et al. (2013) recommended a maximum 30% RAP content in pavement sections constructed from WMA. The Marini batch-mixer asphalt plants currently operational in the UAE and used as a reference case in this study largely manufacture HMA (RAD International Road Construction L.L.C, 2013). However, the lower energy requirements during WMA manufacturing have been modelled as a theoretical alternative option. To allow for lower asphalt production temperatures, synthetic zeolites are used as additive to the WMA mixture at the rate of 0.3% by mass, emissions inventory data for WMA additive is adapted from Vidal et al. (2013). This LCI data for HMA and WMA is shown in Table 1. Following the approach by other studies in pavement literature (Vidal et al., 2013; Cao et al., 2019), the LCI data from the study by Fawer et al. (1998) for the production of synthetic zeolite as WMA additive is used. This life cycle inventory for the production of zeolite as WMA additive is provided in the Appendix (Table A.2). The life cycle inventory for GGBFS production and processing is taken from the Ecoinvent v3.3 database. Inventory for backfill, the pavement courses, and other roadworks materials are taken from the actual material quantity sheet and local UAE material suppliers (Table 2).

Table 2 Materials inventory for the comparative differences between material alternatives, for each component in roadworks

	Water	Sand	Local silica sand	Geotextile fabric (Polypropylene)	20MPa concrete	Gravel	RCW
Virgin backfill: ***AB1***	454.6 $\times 10^3$litres	19.8 $\times 10^3$ m^3	13.10 $\times 10^3$ m^3	93,650 m^2	650 m^3	9,100 m^3	
60% RCW backfill: ***AB2***	454.6 $\times 10^3$litres	19.8 $\times 10^3$ m^3	13.10 $\times 10^3$ m^3	93,650 m^2	650 m^3	3,640 m^3	5,460 m^3

Pavement courses varied between alternates (*material unit: tonnes*)		**Crushed gravel**	**Sand**	**Virgin bitumen**	**Hydrated lime**	**RCW**	**Synthetic zeolite**	**RAP**
Baseline case (virgin HMA & aggregates): ***AP1***	Granular sub-base course	448	-	-	-	-		-
	Unbound-base course	12,600	-	-	-	-		-
	4% bitumen asphalt-base course	6,177	2,901	384.3	144.1	-		-
	4% bitumen asphalt binder course	5,719	2,686	355.8	133.4	-		-
	4.5% bitumen asphalt wearing course	9,242	4,353	650.9	216.9	-		-
80% RCW u-base course: ***AP2***	Unbound-base course	10,080	-	-	-	2,520		-
25% sub-base, 80% RCW u-base course: ***AP3***	Granular sub-base course	336	-	-	-	112		-
	Unbound-base course	10,080	-	-	-	2,520		-
10% RAP a-base, binder & wearing: ***AP4***	4% bitumen asphalt-base course	5,563	2,613	345.9	122.9	-		960.7
	4% bitumen asphalt binder course	5,149	2,419	321.2	113.8	-		889.5
	4.5% bitumen asphalt wearing course	8,331	3,920	585.8	183.7	-		1,446
15% RAP a-base, binder & wearing: ***AP5***	4% bitumen asphalt-base course	5,255	2,469	326.6	116.3	-		1.441
	4% bitumen asphalt binder course	4,865	2,286	302.4	107.6	-		1,334
	4.5% bitumen asphalt wearing course	7,868	3,703	552.5	173.6	-		2,170
25% RAP a-base, 15% RAP binder & wearing: ***AP6***	4% bitumen asphalt-base course	4,640	2,181	288.2	101.8	-		2,402
	4% bitumen asphalt binder course	4,865	2,286	302.4	107.6	-		1,334
	4.5% bitumen asphalt wearing course	7,868	3,703	552.5	173.6	-		2,170

Virgin WMA & virgin aggregates: ***AP7***	Granular sub-base course	448	-	-	-	-		-
	Unbound-base course	12,600	-	-	-	-		-
	4% bitumen asphalt-base course	6,177	2,901	384.3	115.4	-	28.7	-
	4% bitumen asphalt binder course	5,719	2,686	355.8	106.8	-	26.6	-
	4.5% bitumen asphalt wearing course	9,242	4,353	650.9	173.6	-	43.3	-
25% RCW sub-base, 80% RCW u-base, 25% WMA RAP a-base, 15% WMA RAP binder & wearing: ***AP8***	Granular sub-base course	336	-	-	-	112		-
	Unbound-base course	10,080	-	-	-	2,520		-
	4% bitumen asphalt-base course	4,640	2,181	288.2	73	-	28.8	2,402
	4% bitumen asphalt binder course	4,865	2,286	302.4	80.9	-	26.7	1,334
	4.5% bitumen asphalt wearing course	7,868	3,703	552.5	130.2	-	43.4	2,170

Concrete works (*material unit: tonnes*)	**Clinker**	**Gypsum**	**Limestone**	**GGBFS**	**Sand**	**Gravel**
Baseline case concrete works: ***AC1***	416.053	21.897	23.050	-	2,090.330	2,280.153
Alternate/65% GGBFS case concrete works: ***AC2***	216.809	11.387	-	232.806	2,090.330	2,280.153

3.2. Material transportation

Transportation of produced materials from plants to the construction site is conducted using HGVs delivering on roads. The environmental burdens depend upon the fuel consumption efficiency, exhaust emissions, and age of the transporting vehicles. Based on the data from the DoT Abu Dhabi (2009) and Raeside (2015), Euro II diesel articulated trucks are most common in the case study region. Two HGVs were modelled for material transportation: a small (<10 tonnes) truck with a payload capacity of 3.3 tonnes and a medium (10–20 tonnes) truck with a payload capacity of 9.5 tonnes (DSV Global Transport and Logistics, 2019). The type and payload capacity of HGVs is based on the actual field data. Fuel consumption and exhaust emissions of these HGVs were taken from SimaPro databases with the default 100% load factor for the outward journey.

3.3. On-site equipment transportation to the construction site

Road construction sites require different types of equipment: pavers, asphalt rollers, compactors, and excavators, among others. HGVs used for transporting construction equipment to the site were modelled based on the actual case study data and local resources (ADM, 1997; Department of Transport Abu Dhabi, 2018; Maraqa et al., 2018). Three types of articulated trucks were modelled: small (<10 tonnes), medium (10–20 tonnes) and large (>20 tonnes) based on the actual field data. The load factor was based on the actual weight of individual construction equipment being transported.

3.4. Construction

The type of construction machinery used on-site, fuel consumption, fuel-type and the operating hours determine the total environmental impact from this stage. Existing pavement LCA literature (Whyte, 2012; Vidal et al., 2013; Giani et al., 2015; Turk et al., 2016) recommends using local resources to accurately calculate the emissions from this stage. This study used the actual tender document and bill of quantities for the case study highway section project along with local data (Environment Agency - Abu Dhabi, 2012; Department of Transport Abu Dhabi, 2018; Maraqa et al., 2018) to determine the equipment type. Additionally, data from the equipment supplier (Caterpillar Inc., 2011) was used to calculate fuel consumption and operating hours for the construction machinery (Table 3).

Table 3 LCI of construction machinery

Road component	Machinery type and model	Operating time (h)	Fuel Consumption (l/h)
Site excavation	Caterpillar 972H wheel-loader	39	21
Backfill – aggregates	Caterpillar 844 compactor	19.5	62
	Caterpillar 939C track-loader	39	15
Backfill – silica sand	Caterpillar 939C track-loader	78	15

Geotextile fabric	Caterpillar D6K track-type tractor	39	21.5
Utility marking	Caterpillar 966H wheel-loader	19.5	16.9
Granular sub-base course	Caterpillar 844 compactor	19.5	62
Unbound-base course	Caterpillar 966H wheel-loader	19.5	16.9
	Caterpillar 416E loader	117	11.4
Asphalt-base course	Caterpillar CB-434D compactor	780	11.4
Asphalt binder course	Caterpillar CB-434D compactor	780	11.4
Asphalt wearing course	Caterpillar AP-800D paver	780	28.4
Asphalt prime coat	Caterpillar CB-564D compactor	780	10.45
Asphalt tack coat	Caterpillar 345D excavator	390	45.6
Bituminous surface treatment	Caterpillar TH560B articulated trucks	234	15
Milling machine	Caterpillar PM622 cold planner	396	76
Concrete works	Caterpillar dump-trucks 6x4 12 cub.yd	250	20.2
	Caterpillar CP-663E	500	19
	Caterpillar water-truck 4000Gal.	250	14.2

3.5. Applying LCA in construction, maintenance and rehabilitation stages emissions

Routine maintenance involves pavement skin patching, repairing concrete barriers and kerbs, etc. (Stripple, 2001). Rehabilitation is a major maintenance activity to dismantle and replace the pavement course(s) that have reached the end-of-life due to wear and tear. The frequency and extent of repair works are based on the pavement section, strength, daily traffic load, weather cycles and availability of funds to the local municipality. Celauro et al. (2017) considered repaving of asphalt wearing course after every 4 years. Scheving (2011) note that for an asphalt road supporting heavy traffic load (>12,000 vehicles/day/lane), the wearing course should at least be replaced every 6 years. Due to the high strength of asphalt base course compared to the unbound-base course (Rys et al., 2017; Pavement Interactive, 2019) and the difference between service life of different pavement sections (Huang, 2007), the rehabilitation frequencies are also different. Considering these factors, the current study assumes only wearing course milling and repaving after every 5 years due to: traffic load on the case study highway section (>12,000 vehicles/day), thick asphalt base section, budgeting constraints and current practice in the field. Since the M&R stage again involves material extraction and processing, material and equipment transport and construction equipment operation, the LCI of these stages (Tables 1–3) is used including the dismantling/milling equipment used after the end-of-life of the wearing course section.

4. Life cycle impact assessment (results) and interpretation (discussion)

Life cycle impact assessment (LCIA) calculates and provides the environmental impact results of the case study functional unit based upon the earlier established LCI and the selected assessment method. ReCiPe midpoint method can calculate environmental impacts across the indicators in Table 4 (Goedkoop et al., 2009; Hasan et al., 2019b). ReCiPe assesses environmental impacts by three different perspectives of *individualist* (I), *hierarchist* (H) and *egalitarian* (E). Hierarchist perspective is used in this study based on the scientific consensus with regards to technology development, adaption capacity and time-frame (Vidal et al., 2013; PRé Consultants, 2018). The results relating to the *environmental impact reduction effects* of different alternate options are presented below.

Table 4 Environmental impact reduction results, % reduction compared to the baseline case

Environmental impact indicators	Pre-construction earthworks	Asphalt pavement section (*%reduction compared to virgin HMA & virgin aggregates case*)							Concrete works (*% reduction compared to Portland cement case*)	
	AB2 (*% reduction compared to virgin backfill case*)	**AP2**	**AP3**	**AP4**	**AP5**	**AP6**	**AP7**	**AP8**	**AC2 - barriers & kerbs**	**AC2 - traffic & light systems**
Global warming potential (GWP)	16.33%	1.3%	1.41%	3.96%	5.93%	7.05%	6.23%	14.75%	26.37%	3.19%
Stratospheric ozone depletion (OD)	16.2%	0.61%	0.66%	6.25%	9.34%	11.09%	0.20%	11.99%	5.53%	0.11%
Ionizing radiation (IR)	24.77%	0.61%	0.67%	5.02%	7.53%	8.94%	0%	9.61%	5.76%	0.27%
Photochemical ozone formation (POzF)	18.29%	2.50%	2.71%	3.57%	5.53%	6.46%	1.86%	11.11%	12.28%	0.98%
Particulate matter formation (PMF)	14.26%	0.83%	0.91%	3.69%	5.57%	6.58%	2.35%	9.88%	7.49%	0.22%
Photochemical oxidants formation (POxF)	18.26%	2.44%	2.64%	3.7%	5.7%	6.67%	1.83%	11.22%	12.2%	0.96%
Acidification	14.54%	0.94%	1.02%	3.76%	5.69%	6.71%	0.87%	8.65%	9.47%	0.27%
Freshwater eutrophication	15.6%	0.18%	0.2%	1.04%	1.55%	1.85%	0%	2.05%	0.49%	0.96%
Marine eutrophication	14.59%	0.24%	0.26%	1.6%	2.4%	2.85%	0%	3.11%	0.63%	0.90%
Terrestrial eco-toxicity	17.37%	0.3%	0.32%	0.52%	0.78%	0.93%	0.05%	1.31%	0.66%	0.95%
Freshwater eco-toxicity	16.45%	0.07%	0.08%	0.43%	0.65%	0.77%	0%	0.85%	0.29%	0.81%
Marine eco-toxicity	16.53%	0.08%	0.09%	0.47%	0.71%	0.84%	0%	0.93%	0.34%	0.83%
Human toxicity (HT)	15.9%	0.07%	0.08%	0.39%	0.57%	0.69%	0.01%	0.78%	0.64%	0.90%
Land use	9.31%	0.22%	0.24%	6.74%	10.11%	11.99%	0%	12.23%	0.37%	0.62%
Mineral resource depletion	17.28%	0.49%	0.58%	0.57%	0.85%	1.02%	0%	1.0%	6.46%	0.13%
Fossil fuel depletion (FFD)	17.39%	0.66%	0.72%	6.96%	10.43%	12.36%	1.92%	15.02%	13.68%	0.68%
Water consumption	0.32%	0.35%	0.69%	1.83%	2.75%	3.27%	0.05%	1.46%	0.34%	0.94%

4.1. Pre-construction alternate material option – RCW for pavement backfill

The LCA results for the pre-construction earthworks show that significant environmental impacts are generated from this stage (Table 4). Initially, the baseline GWP impact was 2,901.41 tonnes CO_2eq. for the earthworks stage. After 60% replacement of crushed gravel aggregates by RCW as the backfill material in *AB2* case, the GWP impact reduced by 16.33% (2,427.64 tonnes CO_2eq.). FFD exhibited a similar trend with the impact value decreasing to 32.98 TJ from 27.25 TJ, around 17.39% lower. The overall observation was that the environmental impact reduction ranged from 0.32% to 24.77%. The lowest impact reduction (0.32%) was noted for water consumption while IR impacts were reduced by 24.77%.

These results were expected due to the following reasons. Firstly, quarry machinery uses fossil fuel which was reduced with the addition of RCW. Secondly, the transport distance of the RCW processing plant was lower (~70km) than the virgin aggregate production plant (~300km). On the other hand, water consumption impact mainly arises from the water required for aggregate plant operations which are similar for both backfill material alternatives. The significant difference in IR between the two backfill alternatives was because of the excess steel required for quarry operations and production. Significant quantities of NO_x are generated due to electricity consumption in crushing and screening RCW. However due to transport distance variations; significant reduction was found in POxF (18.26%), POzF (18.29%) and eutrophication (14.59%) indicators. Land use impact reduction was 9.31% as the infrastructural requirements are lower for recycling construction waste, which minimises the agricultural land damage.

4.2. Alternate material for pavement section – RCW sub-base and unbound-base

The environmental impact assessment results of the pavement work using baseline case materials exhibited that around 127.55 tonnes CO_2eq. (3.86%) GWP and 1.584 TJ (1.7%) FFD are caused by the use of crushed gravel as sub-base and u-base aggregate material. In order to estimate the impact of reducing crushed gravel use, two different RCW cases were studied: u-base with 80% RCW in the *AP2* case; and 25% RCW sub-base with 80% RCW u-base in the *AP3* case. Similar to Section 4.1 results, partially (80%) replacing crushed gravel by RCW for u-base resulted in a GWP reduction of 54.805 tonnes CO_2eq. and 0.687 TJ decline in FFD.

The environmental impacts were slightly reduced with the additional replacement of gravel in sub-base course by 25% RCW. The GWP reduction in the *AP3* case was 4.93 tonnes CO_2eq. higher than the 80% RCW u-base course case. Likewise, the POzF impact difference was 35.27 kg NO_xeq. (0.213%) and the FFD difference was 0.062 TJ (0.06%). It can be implied from these results that once an optimum material replacement for crushed gravel has been achieved in the sub-base and u-base courses, any further replacement may not yield a significant reduction in the environmental impacts.

4.3. Pavement alternate material option – reclaimed asphalt pavement (RAP)

Three asphalt pavement recycling cases were investigated using different RAP percentages with virgin crushed aggregates for sub-base and u-base courses. Initially, 10% RAP content was used for a-base, binder, and wearing courses in the *AP4* case. Results showed that land use impacts were decreased by 6.74% and OD reduced by 6.25% compared to the baseline case. GWP declined by 167.424 tonnes CO_2eq. (3.96%) and the energy consumption in terms of FFD reduced by 7.23 TJ (6.96%). These reductions in the environmental impacts can be attributed to the difference in the needs for quarry operations and asphalt binder processing, and the less transport distance required for RAP compared to the virgin aggregates. Regarding the use of 15% RAP content in asphalt courses for the *AP5* case, higher environmental impact reduction results were obtained (Table 4). For this case, GWP decreased by 250.601 tonnes CO_2eq. (5.93%), OD by 9.34%, land use by 10.11% and energy consumption by 10.43%; this was again primarily due to differences in asphalt binder production between the different alternatives.

Building on these results, the RAP content in the asphalt mix for the a-base course was increased by another 10% RAP in the *AP6* case. The reduction in FFD and air emissions in this case (25% RAP a-base, 15% RAP binder & wearing courses) compared to the baseline (*AP1*) case are shown in Table 4. FFD exhibited the highest reduction with 12.84 TJ (12.36%) lower value than the baseline *AP1* case. It was then followed by land use (11.99%), OD (11.09%) and GWP (7.05%). Consequently, due to the overall impact reduction from RAP usage for the *AP6* case, the RAP content for this case was flagged as best performing across all midpoint impact categories.

4.4. Pavement alternate asphalt production temperature – warm-mix asphalt (WMA)

After only comparing WMA (containing zeolite additives) and HMA pavement sections, i.e., cases *AP7* and *AP1* in Table 4 respectively, it was observed that the air emissions and energy consumption were only slightly reduced. The volume of natural gas fuel in the asphalt plant reduced due to the lower heating requirements. However, the production of synthetic zeolite additives may have increased the impacts from the material production and processing stage. Overall, the life cycle impacts from WMA were only marginally less than HMA. The life cycle energy consumption reduced by 1.996 TJ (1.92%) while GWP reduced by 6.23% in the *AP7* case compared to the baseline *AP1* case, as shown in Table 4. Impact reduction for POzF and POxF exhibited similar trends with a respective difference of 0.316 tonnes NO_xeq. (1.86%) and 0.322 tonnes NO_xeq. (1.83%) between *AP1* and *AP7*, for these two indicators. These differences in the environmental damages were due to the differences between fuel requirements. Other impact categories, e.g., IR, eutrophication, eco-toxicity, and land use were not affected. Thus, even though the use of WMA reduced environmental impacts to some degree, its real potential is coupling WMA with high RAP content and other material alternatives to achieve reduction across all indicators. These results are similar to the findings by Vidal et al. (2013), where the GWP

reduction between HMA and zeolite-based WMA was only 13%. Butt and Birgisson (2016) also showed that due to the production of additives for WMA mixtures, the difference in life cycle GWP between hot-mix and warm-mix samples was only 12% and the difference in energy consumption was only 2.58%.

4.5. Collective environmental benefits of alternate options on pavement construction

The above results showed that using recycled materials as the alternate option and replacing HMA by WMA as the production technique individually yielded significant environmental impact reduction. The collective environmental impact reduction for the best performing RCW and RAP percentages is now assessed coupled with WMA in the *AP8* case. As shown in Table 4, energy consumption exhibited the highest reduction as FFD decreased by 15.61 TJ (15.02%). The OD was reduced by 11.99%, the POxF reduced by 1.968 tonnes NO_xeq. (11.22%) and PMF by 0.801 tonnes $PM_{2.5}$eq. (9.89%).

GWP impact was also significantly reduced compared to the baseline pavement (*AP1* case), exhibiting 623.54 tonnes CO_2eq. (14.75%) reduction. These environmental impact reductions were contributed by both alternative material usage across the pavement sections and the lower production temperatures of WMA. However, the 12.23% (20,750.65 m2a crop eq.) reduction in land use impact was only attributable to RCW and RAP usage. Water consumption, freshwater, and marine eco-toxicity impacts were only marginally reduced with a respective reduction of 1.46%, 0.85%, and 0.93%. Crushing, screening and producing RCW at recycling plants consumed water volume similar to gravel production. Similarly, construction waste from bricks, etc. is sometimes covered in paint which contains lead and other heavy metals that generate leachate and cause groundwater contamination.

4.6. Traffic barriers, signs, kerbs and light systems – alternate options for concrete works

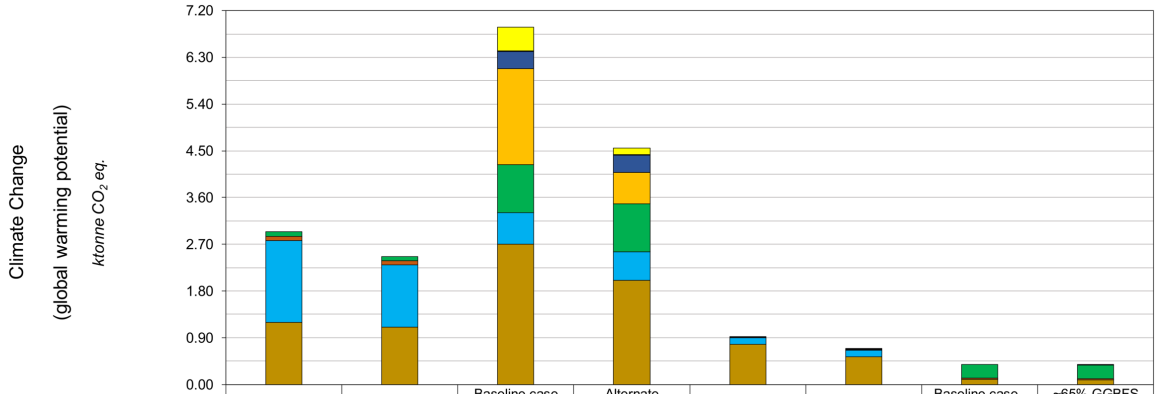
In order to perform a comprehensive environmental impact reduction assessment on the use of alternate options for roadworks in the case study region, partial replacement (~65%) of OPC by GGBFS was performed in the *AC2* case (Table 4). GGBFS generated higher benefits for barriers and kerb works compared to foundation works for traffic signs and light due to the higher volume of concrete used for constructing the former roadworks component.

The GWP results above show that the primary contributor to greenhouse gases is the OPC content in the concrete mix as the impact value reduced by 241.75 tonnes CO_2eq. (26.37%) for traffic barrier and kerbs, and by 12.03 tonnes CO_2eq. (3.2%) for traffic signs and light foundation works. FFD results for traffic kerbs and barriers reduced by 13.68% with GGBFS introduction as they were influenced by mining operations for OPC admixtures: gypsum, clinkers, and limestone. Due to the heavy energy consumption involved in kiln heating during clinker production, GGBFS addition caused a decline in fuel demand. Furthermore, gypsum and limestone mining generates excessive quantities of sulphur dioxide, particulate matter, and nitrogen oxide (NO_x) pollutants. The environmental impact reduction

results for POzF as 12.28% (0.339 tonnes NO_xeq.), POxF as 12.2% (0.342 tonnes NO_xeq.) and acidification as 9.47% (0.191 tonnes SO_2eq.) were obtained after 65% GGBFS content. These results are also indicative of the effect of OPC admixtures on the overall emissions.

4.7. Environmental impacts and reduction potential distribution across life cycle stages

Environmental impacts for the best performing cases from each alternate option were further investigated in detail to identify the impact reduction for each stage of the pavement and associated roadworks life cycle. The "**alternate pavement materials**" for pavement is based on combining the *AP8* case (Section 4.5) and 85% RAP in WMA *wearing course* only during the M&R stage. The RAP content used for M&R is from milling the case study pavement and is transported to the asphalt plant.

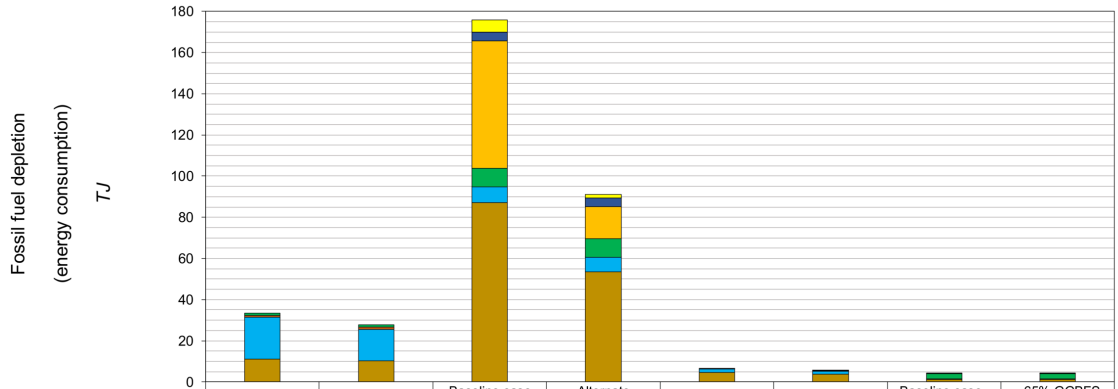


	Earthworks - virgin backfill	Earthworks - 60% RCW backfill	Baseline case pavement materials	Alternate pavement materials	Baseline case - kerbs & parapets	65% GGBFS case - kerbs & parapets	Baseline case - traffic & light systems	~65% GGBFS case - traffic & light systems
Maintenance and Rehabilitation (Const.)	0	0	0.4501	0.1222	6.29E-09	6.29E-09	1.59E-07	1.59E-07
Maintenance and Rehabilitation (Eq. Tran.)	0	0	0.0111	0.0111	4.67E-09	4.67E-09	9.20E-09	9.20E-09
Maintenance and Rehabilitation (Mat. Tran.)	0	0	0.3312	0.3312	7.56E-08	7.56E-08	3.89E-09	3.89E-09
Maintenance and Rehabilitation (RE & P)	0	0	1.8543	0.6105	4.66E-07	3.21E-07	5.87E-08	5.15E-08
Construction	0.0892	0.0892	0.9210	0.9210	0.0105	0.0105	0.2650	0.2650
Equipment Transport	0.0791	0.0791	0.0035	0.0035	0.0078	0.0078	0.0153	0.0153
Material Transport	1.5820	1.1929	0.5996	0.5449	0.1260	0.1260	0.0065	0.0065
Raw Material Extraction and Processing	1.1907	1.1060	2.7059	2.0061	0.7765	0.5348	0.0979	0.0859

Figure 5 Climate change impacts and reduction distribution across life cycle stages

Figure 5 shows that earthworks contribution to total GWP impact of baseline case roadworks (11.123 ktonnes CO_2eq.) was 26% and FFD contribution was 15% to the total FFD of 219.896 TJ. Extraction and processing of crushed gravel and sand backfill caused 40% of the GWP emissions for the earthworks. This contribution was increased (~45%) when 60% RCW was used. However, it was offset by the reduction in material transport contribution to the GWP. For earthworks using virgin backfill materials, transporting materials caused 54% of the GWP emissions which was reduced to 48% with the 60% RCW option. Similar trends were observed for energy consumption results shown in Figure 6 below. A reduction in the material transport FFD share (from 61% to 55%) offset the increase in material extraction and processing share, which had increased to 37% from 33%. In general, material transport remained the largest contributor to the environmental impacts caused during earthworks due to the excessive transport distance from quarries in Fujairah to Abu Dhabi. Environmental impact

contributions of construction equipment transport to the project site remained 3-4% due to the machinery used for this component of the roadworks.



	Earthworks - virgin backfill	Earthworks - 60% RCW backfill	Baseline case pavement materials	Alternate pavement materials	Baseline case - kerbs & parapets	65% GGBFS case - kerbs & parapets	Baseline case - traffic & light systems	~65% GGBFS case - traffic & light systems
Maintenance and Rehabilitation (Const.)	0	0	5.8057	1.5987	3.39E-06	3.39E-06	6.88E-05	6.88E-05
Maintenance and Rehabilitation (Eq. Tran.)	0	0	0.1425	0.1425	2.51E-06	2.51E-06	4.94E-06	4.94E-06
Maintenance and Rehabilitation (Mat. Tran.)	0	0	4.2501	4.2501	4.06E-05	4.06E-05	2.09E-06	2.09E-06
Maintenance and Rehabilitation (RE & P)	0	0	61.7258	15.4506	1.15E-04	9.29E-05	2.81E-05	2.74E-05
Construction	1.1503	1.1503	9.0981	9.0981	0.1351	0.1351	2.7391	2.7391
Equipment Transport	1.0154	1.0154	0.0444	0.0444	0.0999	0.0999	0.1967	0.1967
Material Transport	20.2992	15.3059	7.6933	6.9918	1.6163	1.6163	0.0831	0.0831
Raw Material Extraction and Processing	11.0314	10.2881	87.0820	53.5616	4.5696	3.6979	1.1179	1.0905

Figure 6 Fossil fuel depletion impacts and reduction distribution across life cycle stages

Pavement section works generated 62% of GWP and 80% of the FFD impact caused by the complete baseline case. For the impact distribution within the pavement section works, raw material extraction and processing stage was the largest contributor. The environmental impacts were considerably reduced between baseline case pavement section and alternate materials case. This was mainly due to less raw materials demand for aggregates and bitumen and shorter transport distance. The share of raw material sub-stage within the M&R stage was also considerably reduced between the baseline case (27%) and alternate pavement materials case (13%). These results were caused by using recycled RAP and WMA for initial construction, followed by recycling the milled RAP (from case study pavement section's wearing course) in the mixing plant and then used for repaving. Overall, the GWP for pavement section works reduced by 34% (2.33 ktonnes CO_2eq.) while FFD reduced by 48% (84.71 TJ), with the most significant reductions in the material extraction and M&R stages.

The concrete barriers, kerbs and parapets works were responsible for 8% of the GWP and 3% of FFD impacts. The majority (84%) of their GWP and FFD (71%) contributions were caused by material extraction and processing stage. The use of GGBFS considerably reduced these impacts as shown in Figure 5 and Figure 6. The GWP share from this stage reduced to 79% while the FFD contribution decreased to 67%. On the other hand, concrete foundations for the traffic signs and light systems were the only component of the roadworks where the construction stage generated the highest environmental impacts during the studied life cycle. This is due to the diesel fuel consumed for operating the heavy on-site construction machinery.

4.8. Uncertainty assessment

PRé Consultants (2016) specify that due to the extent of the large inventory data, a certain degree of uncertainty is introduced in the LCA results because of the uncertainties in LCI data. Accurately acknowledging for these uncertainties is specifically important when two alternates are being compared, as any projected environmental impact reduction benefits of alternate cases can be offset by uncertain input data. Monte Carlo simulations are performed to calculate the uncertainty distribution for each indicator in the *alternate materials case for pavement works* (Section 4.7) and results are as shown in Table 5 with a 95% confidence interval, i.e., 95% of the LCIA results fall in the "2.5th percentile" and "97.5th percentile" probability distribution range (Guo and Murphy, 2012). The coefficient of variability scores for majority of the indicators exhibited low variance. However, the scores for ionizing radiation, water consumption and indicators related to eco-toxicity showed high degree of variance. This high degree of uncertainty may have been caused by the different input sources (for water consumption indicator) and the uncertainties in the database for heavy metal emissions (for eco-toxicity and IR indicators), as also found by Guo and Murphy (2012). Nonetheless, the LCIA results for GWP, OD, POzF, PMF, POxF, acidification, eutrophication, HT, land use, FFD and mineral resource depletion showed high a degree of certainty, as exhibited by the CV scores in Table 5.

Table 5 Monte Carlo uncertainty assessment results for alternate materials[ɟ] case (pavement works)

Impact category	Unit	Mean	Coefficient of Variability (CV)	2.5th percentile	97.5th percentile
Global warming potential (GWP)	kg CO_2 eq.	4.91E+06	5.12%	4.44E+06	5.43E+06
Stratospheric ozone depletion (OD)	kg CFC11 eq.	2.38E+00	20.9%	1.79E+00	3.71E+00
Ionizing radiation (IR)	kBq Co-60 eq.	1.72E+05	64.96%	3.88E+04	7.11E+05
Photochemical ozone formation (POzF)	kg NO_x eq.	2.53E+04	7.53%	2.17E+04	2.95E+04
Particulate matter formation (PMF)	kg $PM_{2.5}$ eq.	9.31E+03	7.39%	8.14E+03	1.10E+04
Photochemical oxidants formation (POxF)	kg NO_x eq.	2.58E+04	7.45%	2.22E+04	3.02E+04
Acidification	kg SO_2 eq.	2.47E+04	8.69%	2.12E+04	2.98E+04
Freshwater eutrophication	kg P eq.	2.56E+03	34.5%	1.39E+03	5.96E+03
Marine eutrophication	kg N eq.	1.56E+02	23.5%	1.05E+02	2.49E+02
Terrestrial eco-toxicity	kg 1,4-DCB	5.25E+07	36.1%	2.89E+07	1.02E+08
Freshwater eco-toxicity	kg 1,4-DCB	4.19E+05	62.3%	1.19E+05	1.32E+06
Marine eco-toxicity	kg 1,4-DCB	6.06E+05	60.08%	1.84E+05	1.90E+06
Human toxicity (HT)	kg 1,4-DCB	1.49E+07	38.1%	3.57E+06	5.03E+07
Land use	m2a crop eq.	1.70E+05	11.1%	1.38E+05	2.10E+05
Mineral resource depletion	kg Cu eq.	4.95E+04	8.4%	4.23E+04	5.86E+04
Fossil fuel depletion (FFD)	TJ	1.05E+02	11.7%	8.41E+01	1.32E+02

Water consumption	m^3	2.79E+05	70.8%	2.27E+06	2.32E+06

ǂ Combining AP8 (*25% RCW sub-base, 80% RCW unbound-base, 25% WMA RAP asphalt-base and 15% WMA RAP binder & wearing courses*) for initial construction & 85% in-plant recycled WMA RAP in M&R stage

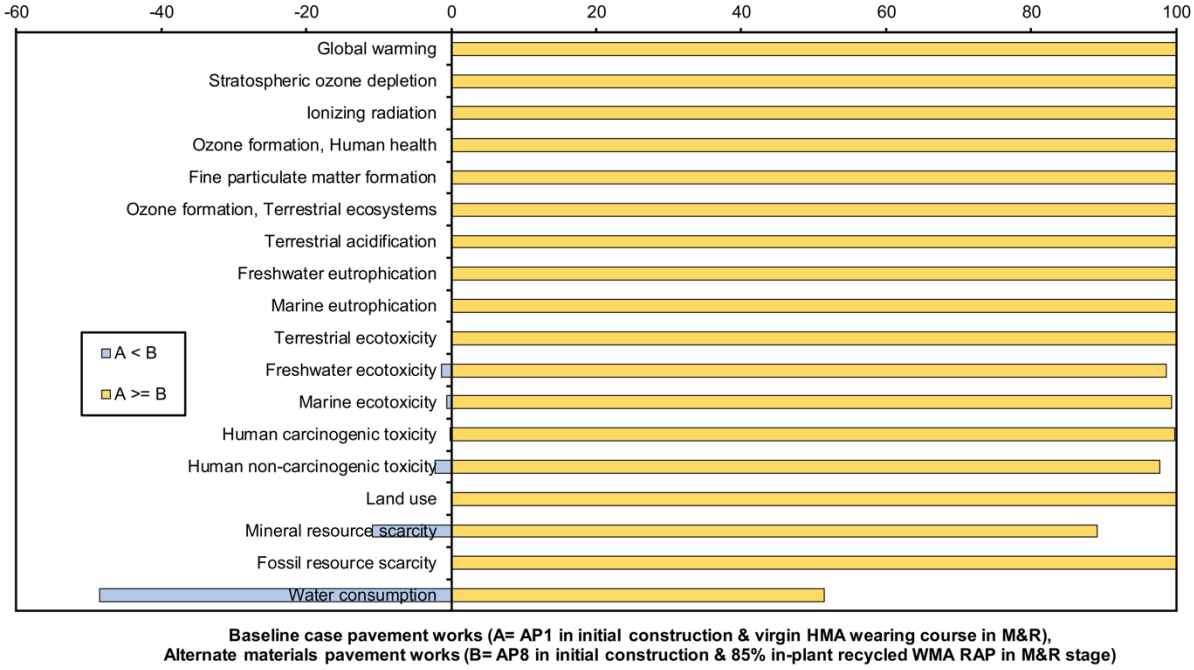


Figure 7 Monte Carlo uncertainty assessment results for pavement works, "baseline case" against "alternate materials case"

Monte Carlo simulations are performed to calculate the probability of environmental impacts from the "*alternate materials pavement works (B)*" case to be lower than the "*baseline pavement works (A)*" case, with 95% confidence interval. For each case, the simulation consisted of 1,000 iterations. Figure 7 reports the comparison between Monte Carlo simulation results for the baseline and alternate materials pavement works. These results are also tabulated in Appendix (Table A.3) for further clarification. The probability that the impact values for *alternate pavement materials* case are lower than the *baseline* case is in the 90%–100% range for the majority of indicators. However, the water consumption impact for the baseline case pavement works was higher than the "alternate materials case" in 52% of the simulated cases. This is due to the volume of water required for producing RCW at construction waste recycling facilities; which is obtained from a variety of freshwater, marine and wastewater resources that can amplify the uncertainties in input data. Figure 8 reports the Monte Carlo simulation results for the GWP impacts generated by concrete works. The coefficient of variation (CV) values are admissible. CV values for concrete works conducted as part of kerbs, parapets and barriers ranged between 6.01% – 6.7%. For the concrete roadworks due to traffic signs and light system foundations, the CV values ranged from 3.8% – 3.9%

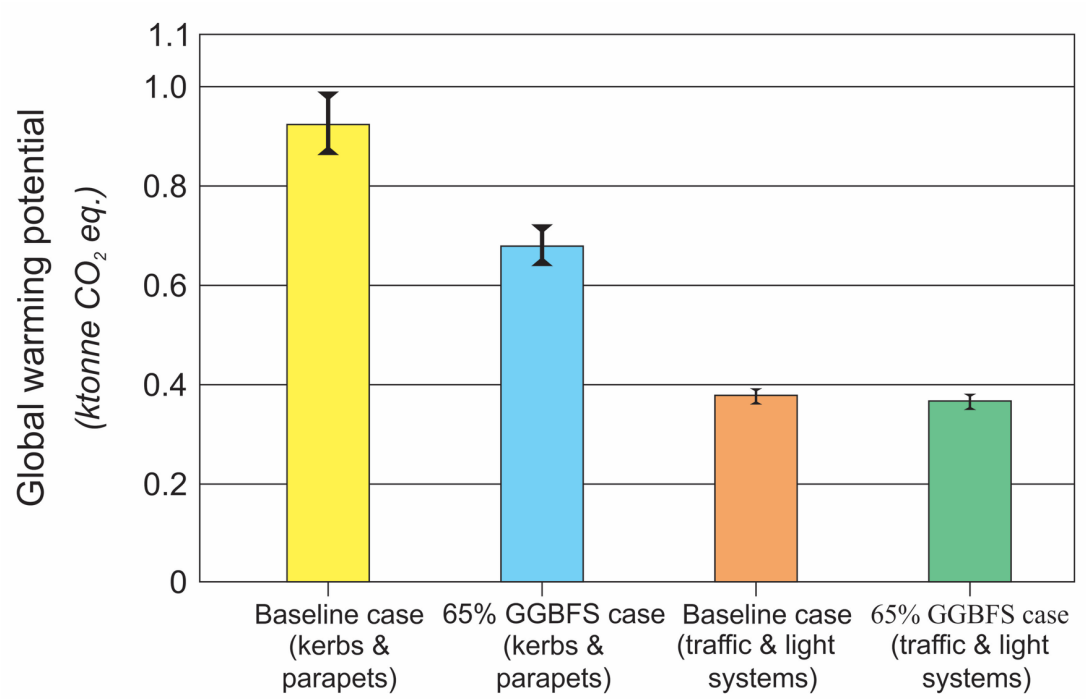


Figure 8 Global warming potential uncertainty assessment for concrete works, baseline vs. alternate case

4.9. Sensitivity analysis of LCA allocation method

The current study applied a 100:0 allocation approach to the use of recycled materials (RAP and RCW) in the "alternate" cases. This means that the current study assigned all environmental burdens associated with the material extraction and production etc. are assigned to the original pavement using the virgin materials and it is not credited with any potential recycling (e.g., in form of RAP) after it has reached its end-of-life. On the other hand, pavements using recycled materials (e.g., RAP and RCW) carry the burden of processing after initial use and are also fully credited with the benefit of using recycled materials. Wayman et al. (2013) propose that the potential recyclability of asphalt to produce RAP content for future use is high and the recoverability rate needs to be optimised for providing benefit to the subsequent asphalt production mix. However, the resulting benefits of recycled material use may be influenced by the allocation methodology and a sensitivity analysis for allocation of recycled materials needs to be performed in addition to the uncertainty assessment for the LCA data.

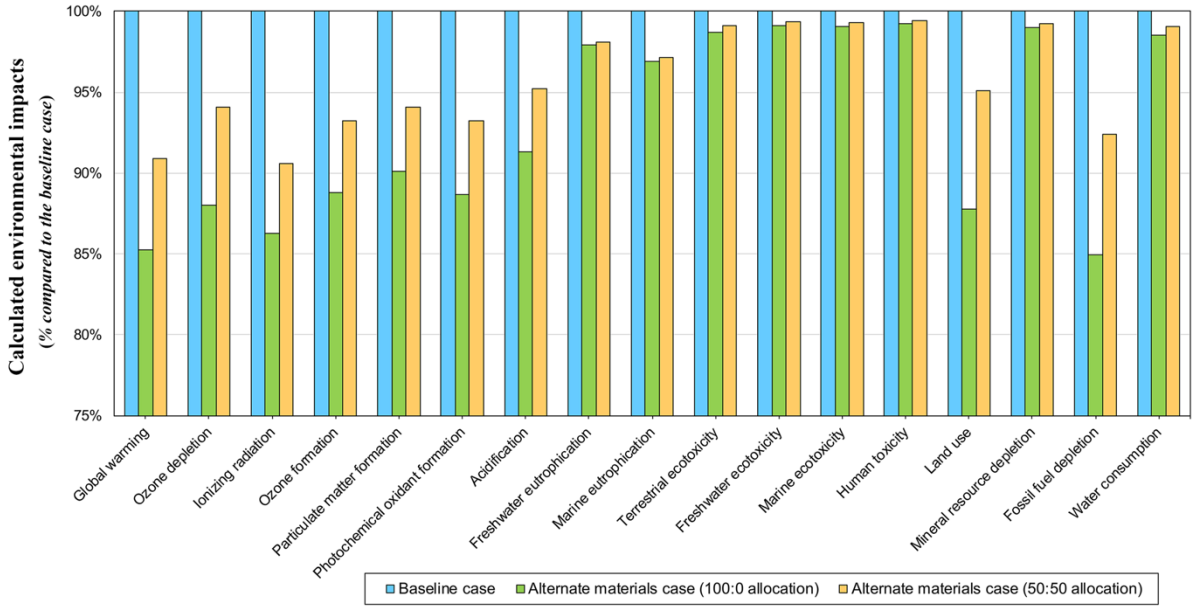


Figure 9 Sensitivity analysis of pavement works with 100:0 and 50:50 allocation

(Baseline case: virgin HMA & aggregates; *Alternate materials case: recycled RCW & RAP courses as defined in Section 4.7)*

In the current study, a majority of GWP (~62%) and energy use (~80%) burdens were generated by the asphalt courses, which were reduced after recycled RAP was used. As open-loop RAP recycling (i.e., RAP from an external older pavement) was used in the initial construction stage, the results can be sensitive to the allocation approach. A sensitivity analysis was thus performed for the pavement works, focusing on the allocation of RAP burdens. The 50:50 allocation methodology is an alternate to the 100:0 approach, where the environmental burdens of raw material extraction and processing of the recycled materials are shared equally between both pavement systems (i.e., the original pavement producing the RAP and the current pavement using the recycled RAP as an alternate material option). Figure 9 presents the results of sensitivity analysis for the pavement works based on the two allocation methodologies of 100:0 (as used in current study) and 50:50 (where half of the raw materials' burdens for the asphalt mix generating the recycled RAP used in the alternate material case are assigned to the case study pavement works).

The results show that the allocation methodology for the recycled RAP somewhat affects the environmental benefits gained by using recycled materials for constructing the case study pavement section. The difference in the environmental reduction (due to the use of recycled materials) between the "100:0" allocation (as used in current study) and the "50:50" allocation is in the range of 0.13–7.44%, compared to the baseline case. The FFD indicator was the most influenced by the allocation approach with a difference of 7.73 TJ (~7.44%), followed by land use (7.3%), OD (6.1%), and GWP (5.7%). Conversely, freshwater eutrophication (0.13%), human toxicity (0.2%), and ecotoxicity-related indicators were the least affected. Overall, using recycled materials for pavement construction may be

environmentally favourable, however, the absolute benefit may be dependent upon the allocation methodology selected for reporting the LCA results. In general, the environmental benefit from using recycled materials (such as RAP) are significantly higher than the difference in the environmental burdens calculated from both allocation methodologies.

5. Case study GWP and FDD impacts and comparison with roadworks LCA literature

The roadworks LCA literature covered in the earlier sections highlights that several studies have assessed the environmental impact reduction in pavement works by using RCW and RAP as alternate material options, and WMA instead of HMA as an alternate production technique. Figure 10 compares the findings of some of these studies against the results of the current study in terms of GWP impact. It shows that the GWP values of this study are at least 29% higher. This difference is attributable to the consumption of higher bitumen consumption for case study highway section than the studies (Biswas, 2014; Giani et al., 2015; Celauro et al., 2017) in Figure 10. The *alternate materials case* for Biswas (2014) uses 100% RCW (base course) to replace crushed natural gravel in initial construction stage and recycled limestone (sub-base course), 100% RCW (base course) and 15% RAP (wearing course) in the M&R stage. For Giani et al. (2015), the *alternate materials case* utilised 30% WMA RAP (base course), 20% HMA RAP (binder course) and 10% HMA RAP (wearing course) during initial construction; and, 100% in-plant recycled wearing course in M&R stage. The *alternate materials case* for Celauro et al. (2017) consisted of lime-stabilised embankment, 100% RCW sub-base course, 40% RAP base course, 40% RAP binder course and 15% RAP wearing course.

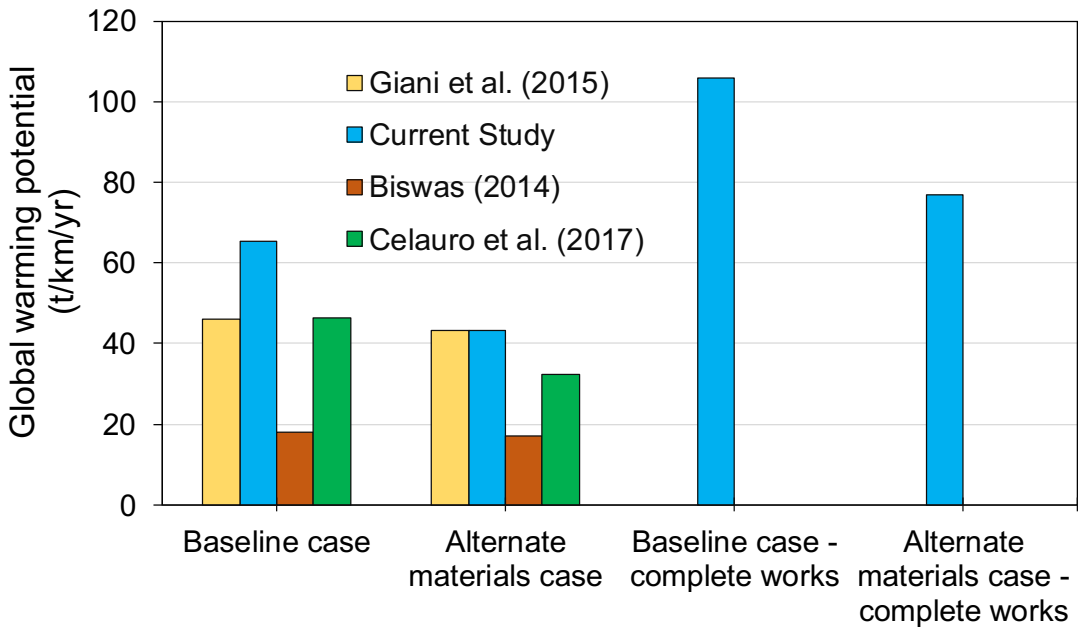


Figure 10 Comparative assessment of global warming results, road LCA against the current study

The "alternate materials case" for the current study uses RCW, RAP and WMA for backfill, pavement works; combining *AB2* and *AP8* (with 85% in-plant recycled WMA RAP in M&R stage as stated in Section 4.7). Similarly, "alternate materials case – complete works" for the current study also included GGBFS as partial replacement of Portland cement (~65%) after combining this "*alternate materials case*" and *AC2*. This way, the impacts for complete roadworks are included: earthworks, pavement courses, concrete works for traffic barriers, kerbs, parapets, traffic signs, and light systems.

However, the current study also reported a significantly higher reduction in GWP emissions after using WMA combined with alternate material options (RCW and RAP). In the current study, GWP impact for pavement section works reduced by 34%, whereas Giani et al. (2015) reported a 6% reduction in GWP after using both WMA and RAP. Biswas (2014) reported a 5% reduction after using RCW (both during initial construction and M&R stages) and RAP (in M&R stage only). The 30% GWP impact reduction reported by Celauro et al. (2017) was comparable to the findings of the current study. These observations further iterate the need for region-based LCA studies as well as the high environmental benefits that can be achieved in the case study region due to the use of low-temperature asphalt mixes (warm and cold mix) and alternate construction material options. The reduced transport distance required for alternate materials, compared to virgin materials, may have also contributed to these results.

6. Conclusion

This study presented a comprehensive LCA of roadworks on a 3.5-km long highway section in Abu Dhabi. Environmental impacts across all components of a road section were accounted: earthworks; pavement section courses; concrete barriers, kerbs and parapets; and, the concrete foundation works for traffic signs and light systems. In general, the raw material stage was the highest contributor to GWP as it generated 63.96% of baseline case emissions. Construction stage accounted for the second highest (~21.78%), followed by material (~14.18%) and equipment transport (0.05%).

The use of RCW as an alternate backfill material holds promise as the GWP value reduced by 16% with the use of 60% RCW. RCW use in sub-base and u-base courses also reduced impacts from asphalt pavement section, for e.g., 59.736 tonnes CO_2eq. reduction in GWP and 11.68 GJ reduction in energy (FFD) impact. However, these reductions only account for approximately 1.4% of the total environmental impacts of the entire pavement sections.

Although the use of WMA instead of HMA reduced environmental impacts, e.g., GWP by 6.23% and FFD by 1.92%, the most notable reductions were due to RAP addition in the WMA asphalt mix. This was primarily due to large environmental burdens associated with production of bitumen, hydrated lime filler and synthetic zeolite additives. The 25% RAP content in the a-base course and the 15% RAP content in binder and wearing courses coupled with WMA resulted in significantly lower environmental

impacts across all indicators. For example, FFD and GWP impact values decreased in the order of 15%. Two options were compared during the rehabilitation stage of milled wearing course. As an important advantage of WMA is the potential to use high RAP content in the production mix, 85% in-plant WMA recycling of milled RAP was assessed against virgin HMA asphalt. This resulted in the reduction of GWP by 59% and FFD by 70%. Comparing baseline OPC-concrete for roadworks against GGBFS-concrete, GWP exhibited the highest reduction (~19%) followed by FFD (~9%), POxF (~8.4%), POzF (~8.3%) and acidification (6.12%).

These results of the current study were also assessed against those reported in pavement LCA literature. A key advantage of the current study was the higher benefit (e.g., overall 34% for GWP and 48% FFD) of using alternate options compared to previous studies. This is mainly due to the pavement section design, transport distance, material type, and production variations. The uncertainty assessment by Monte Carlo simulation also confirmed that the high environmental impacts of roadworks in the case study region can be reduced by alternate material use to around 99% probability. The results of sensitivity analysis for allocation approach show that the environment benefits of using alternate recycled materials is affected by the allocation methodology selected for reporting the LCA results. However, the sensitivity was lower than the calculated environmental benefit for all the indicators calculated in the current study. It should also be noted that this study only focuses on the environmental impact reduction potential of alternate options (RCW, WMA, RAP and GGBFS) for pavement construction, maintenance and rehabilitation. Future works may include the pollutant emissions from vehicles during construction and M&R (work-zone traffic delays) and use stage with a focus on pavement performance and traffic management strategies.

7. Acknowledgement

This research project is supported by an Australian Government Research Training Program (RTP) scholarship. The authors also thank the Abu Dhabi Municipality for their support and assistance in data collection.

8. References

AASHTO, 2012. Standard specification for use of reclaimed asphalt shingles (RAS) as an additive in hot mix asphalt (HMA). American Association of State Highway Transportation Officials, Washington, DC.

Abdelfatah, A.S., Tabsh, S.W., 2011. Review of Research on and Implementation of Recycled Concrete Aggregate in the GCC. Advances in Civil Engineering 2011, 6.

Abergel, T., Dean, B., Dulac, J., 2017. Towards a zero-emission, efficient, and resilient buildings and construction sector: Global Status Report 2017. United Nations Environment and International Energy Agency, Paris, France, p. 43.

Abou-Senna, H., Radwan, E., Westerlund, K., Cooper, C.D., 2013. Using a traffic simulation model (VISSIM) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway. Journal of the Air & Waste Management Association 63(7), 819-831.

Abu Dhabi City Municipality, 2010. Sustainability Guideline for Abu Dhabi Municipality, IRI Employees and Consultants, in: Section, P.R.a.I.D. (Ed.). Abu Dhabi Municipality, Projects Roads and Infrastructure Design Section, Abu Dhabi, United Arab Emirates, p. 71.

ADM, D.o.M.A.A.D.M.-. 1997. Standard specifications for road and bridge construction. Abu Dhabi Municipality, Abu Dhabi, UAE, p. 652.

Almeida-Costa, A., Benta, A., 2016. Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt. Journal of Cleaner Production 112, 2308-2317.

Alzard, M.H., Maraqa, M.A., Chowdhury, R., Khan, Q., Albuquerque, F.D.B., Mauga, T.I., Aljunadi, K.N., 2019. Estimation of Greenhouse Gas Emissions Produced by Road Projects in Abu Dhabi, United Arab Emirates. Sustainability 11(8), 2367.

Anastasiou, E.K., Liapis, A., Papayianni, I., 2015. Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. Resources, Conservation and Recycling 101, 1-8.

AzariJafari, H., Yahia, A., Ben Amor, M., 2016. Life cycle assessment of pavements: reviewing research challenges and opportunities. Journal of Cleaner Production 112, 2187-2197.

Balaguera, A., Carvajal, G.I., Albertí, J., Fullana-i-Palmer, P., 2018. Life cycle assessment of road construction alternative materials: A literature review. Resources, Conservation and Recycling 132, 37-48.

Bank, W., 2019. CO_2 emissions (metric tons per capita), 2014 ed. Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States.

Batouli, M., Bienvenu, M., Mostafavi, A., 2017. Putting sustainability theory into roadway design practice: Implementation of LCA and LCCA analysis for pavement type selection in real world decision making. Transportation Research Part D: Transport and Environment 52, 289-302.

Biswas, W.K., 2014. Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. The International Journal of Life Cycle Assessment 19(4), 732-744.

Blankenagel, B.J., 2005. Characterization of recycled concrete for use as pavement base material, Department of Civil and Environmental Engineering. Brigham Young University, Provo, Utah, p. 66.

Blengini, G.A., Garbarino, E., 2010. Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. Journal of Cleaner Production 18(10), 1021-1030.

Butt, A.A., Birgisson, B., 2016. Assessment of the attributes based life cycle assessment framework for road projects. Structure and Infrastructure Engineering 12(9), 1177-1184.

Butt, A.A., Mirzadeh, I., Toller, S., Birgisson, B., 2014. Life cycle assessment framework for asphalt pavements: methods to calculate and allocate energy of binder and additives. International Journal of Pavement Engineering 15(4), 290-302.

Cao, R., Leng, Z., Yu, H., Hsu, S.-C., 2019. Comparative life cycle assessment of warm mix technologies in asphalt rubber pavements with uncertainty analysis. Resources, Conservation and Recycling 147, 137-144.

Caterpillar Inc., 2011. Caterpillar Performance Handbook 41. Caterpillar Incorporated, Peoria, Illinois, p. 1474.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., Rizzo, A., 2017. Environmental analysis of different construction techniques and maintenance activities for a typical local road. Journal of Cleaner Production 142, 3482-3489.

Department of Transport Abu Dhabi, 2018. Standard construction specifications part 1, 1st ed. Department of Transport Abu Dhabi, Abu Dhabi, UAE, p. 1124.

DoT Abu Dhabi, 2009. Surface Transport Master Plan - A Vision for Connecting Abu Dhabi. Abu Dhabi, United Arab Emirates, p. 171.

DSV Global Transport and Logistics, 2019. Trucks and trailers types. http://www.ae.dsv.com/road-freight/trailer-types-and-dimensions/. (Accessed 09/06/2019 2019).

Elchalakani, M., Aly, T., Abu-Aisheh, E., 2014. Sustainable concrete with high volume GGBFS to build Masdar City in the UAE. Case Studies in Construction Materials 1, 10-24.

Environment Agency - Abu Dhabi, 2012. Greenhouse Gas Inventory for Abu Dhabi Emirate - Inventory Results Executive Summary. Environment Agency - Abu Dhabi, Abu Dhabi, UAE, p. 25.

Fawer, M., Postlethwaite, D., Klüppel, H.J., 1998. Life cycle inventory for the production of zeolite a for detergents. The International Journal of Life Cycle Assessment 3(2), 71-74.

Giani, M.I., Dotelli, G., Brandini, N., Zampori, L., 2015. Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. Resources, Conservation and Recycling 104, 224-238.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., Zelm, R., 2009. ReCiPe 2008, PRé Consultants. University of Leiden, Radboud University, RIVM, Nijmegen. Den Haag, The Netherlands: VROM (Dutch Ministry of Housing Spatial Planning and Environment).

Guo, M., Murphy, R.J., 2012. LCA data quality: Sensitivity and uncertainty analysis. Science of The Total Environment 435-436, 230-243.

Guo, S., Hu, J., Dai, Q., 2018. A critical review on the performance of portland cement concrete with recycled organic components. Journal of Cleaner Production 188, 92-112.

Harvey, J., Meijer, J., Ozer, H., Al-Qadi, I.L., Saboori, A., Kendall, A., 2016. Pavement Life Cycle Assessment Framework. United States Federal Highway Administration, Urbana, IL, p. 244.

Hasan, U., 2015. Experimental study on bentonite stabilisation using construction waste and slag, Department of Civil Engineering. Curtin University, Perth, Western Australia, Australia, p. 181.

Hasan, U., Chegenizadeh, A., Budihardjo, M.A., Nikraz, H., 2016a. Experimental Evaluation of Construction Waste and Ground Granulated Blast Furnace Slag as Alternative Soil Stabilisers. Geotechnical and Geological Engineering 34(6), 1707-1722.

Hasan, U., Chegenizadeh, A., Budihardjo, M.A., Nikraz, H., 2016b. Shear Strength Evaluation Of Bentonite Stabilised With Recycled Materials. Journal of GeoEngineering 11(2), 59-73.

Hasan, U., Whyte, A., Al Jassmi, H., 2019a. Life-cycle asset management in residential developments building on transport system critical attributes via a data-mining algorithm. Buildings 9(1).

Hasan, U., Whyte, A., Al Jassmi, H., 2019b. Critical review and methodological issues in integrated life-cycle analysis on road networks. Journal of Cleaner Production 206, 541-558.

Hasan, U., Whyte, A., Al Jassmi, H., 2020. A review of the transformation of road transport systems: Are we ready for the next step in artificially intelligent sustainable transport? Applied System Innovation 3(1), 1-20.

Hill, N., Brannigan, C., Wynn, D., Milnes, R., Van Essen, H., den Boer, E., van Grinsven, A., Ligthart, T., van Gijlswijk, R., 2012. EU Transport GHG: Routes to 2050 II. The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions.

Hoque, N., Biswas, W.K., Mazhar, I., Howard, I., 2019a. Environmental life cycle assessment of alternative fuels for Western Australia's transport sector. Atmosphere 10(7), 398.

Hoque, N., Biswas, W.K., Mazhar, I., Howard, I., 2019b. LCSA framework for assessing sustainability of alternative fuels for transport sector. Chemical Engineering Transactions 72, 103-108.

Huang, Y., 2007. Life Cycle Assessment of Use of Recycled Materials in Asphalt Pavements, School of Civil Engineering and Geosciences. Newcastle University, Newcastle upon Tyne, UK, p. 173.

ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva, Switzerland, p. 20.

ISO 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and guidelines. International Organization for Standardization, Geneva, Switzerland, p. 46.

Kim, T., Tae, S., Chae, U.C., 2016. Analysis of Environmental Impact for Concrete Using LCA by Varying the Recycling Components, the Compressive Strength and the Admixture Material Mixing. Sustainability 8(4).

Lee, K.-M., Inaba, A., 2004. Life cycle assessment: best practices of ISO 14040 series. The APEC Secretariat, Suwon, Korea, p. 99.

Maraqa, M., Chowdhury, R., Mauga, T., Albuquerque, D., Alzard, M., Khan, Q., Kamareddine, L., Sherif, M., 2018. Assessing the Carbon Footprint of Road Projects and Related Sustainability Initiatives in Abu Dhabi. Abu Dhabi City Municipality, Department of Municipal Affairs, Abu Dhabi, UAE, p. 146.

Miliutenko, S., Björklund, A., Carlsson, A., 2013. Opportunities for environmentally improved asphalt recycling: the example of Sweden. Journal of Cleaner Production 43, 156-165.

Moretti, L., Mandrone, V., D'Andrea, A., Caro, S., 2018. Evaluation of the environmental and human health impact of road construction activities. Journal of Cleaner Production 172, 1004-1013.

Pavement Interactive, 2019. https://www.pavementinteractive.org/reference-desk/pavement-types-and-history/pavement-types/asphalt-concrete-base-acb/. https://www.pavementinteractive.org/reference-desk/pavement-types-and-history/pavement-types/asphalt-concrete-base-acb/. (Accessed 10/06/2019 2019).

Praticò, F.G., Vaiana, R., Iuele, T., 2015. Permeable Wearing Courses from Recycling Reclaimed Asphalt Pavement for Low-Volume Roads. Transportation Research Record: Journal of the Transportation Research Board 2474, 65-72.

PRé Consultants, 2016. SimaPro 8.5.2© Manual. PRé Consultants, San Francisco, California, p. 80.

PRé Consultants, 2018. SimaPro Database Manual - Methods Library. PRé Consultants, San Francisco, California, p. 69.

RAD International Road Construction L.L.C, 2013. Asphalt Production. http://rad.ae/site/index.php/en/asphalt-factory/asphaltproduction. (Accessed 09/06/2019 2019).

Raeside, J., 2015. Middle East emissions legislation. https://www.integer-research.com/industry-insight/emissions-legislation/middle-east/. (Accessed 09/06/2019 2019).

Rathje, E.M., Rauch, A.F., Folliard, K.J., Trejo, D., Little, D., Viyanant, C., Ogalla, M., Esfeller, M., 2002. Recycled asphalt pavement and crushed concrete backfill: Results from initial durability and geotechnical tests. Center for Transportation Research, The University of Texas at Austin, Austin, TX, p. 70.

Rys, D., Judycki, J., Pszczola, M., Jaczewski, M., Mejlun, L., 2017. Comparison of low-temperature cracks intensity on pavements with high modulus asphalt concrete and conventional asphalt concrete bases. Construction and Building Materials 147, 478-487.

Santos, J., Ferreira, A., Flintsch, G., 2015. A life cycle assessment model for pavement management: road pavement construction and management in Portugal. International Journal of Pavement Engineering 16(4), 315-336.

SCAD, 2014. Statistical Yearbook of Abu Dhabi. Statistics Centre - Abu Dhabi (SCAD), Abu Dhabi, United Arab Emirates, p. 324.

Scheving, A.G., 2011. Life Cycle Cost Analysis of Asphalt and Concrete Pavements, School of Science and Engineering. Reykjavík University, Reykjavík, Iceland, p. 83.

Stripple, H., 2001. Life cycle assessment of road. A pilot study for inventory analysis, A pilot study for inventory analysis. Rapport IVL S, 2nd ed. IVL – Swedish Environmental Research Institute, Gothenburg, Sweden, p. 96.

Tarefder, R.A., Pan, J., 2014. Field and Laboratory Evaluation of Warm Mix Asphalt (WMA) – Phase 1. University of New Mexico, Albuquerque, NM, p. 147.

Turk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., Jurjavčič, P., 2016. Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction. Journal of Cleaner Production 121, 45-55.

Ventura, A., Monéron, P., Jullien, A., 2008. Environmental Impact of a Binding Course Pavement Section, with Asphalt Recycled at Varying Rates. Road Materials and Pavement Design 9(sup1), 319-338.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resources, Conservation and Recycling 74, 101-114.

Vieira, C.S., Pereira, P.M., 2015. Use of recycled construction and demolition materials in geotechnical applications: A review. Resources, Conservation and Recycling 103, 192-204.

Wang, T., 2013. Reducing greenhouse gas emissions and energy consumption using pavement maintenance and rehabilitation: Refinement and application of a life cycle assessment approach, Civil and Environmental Engineering. University of California, Davis, Ann Arbor, p. 374.

Wayman, M., Schiavi-Mellor, I., Cordell, B., 2013. Protocol for the calculation of whole life cycle greenhouse gas emissions generated by asphalt. Transport Research Laboratory, Berkshire, United Kingdom, p. 40.

Whyte, A., 2012. Life-Cycle Assessment of Built Asset Waste Materials-Sustainable Disposal Options, 1 ed. Lambert Academic Publishing (LAP), Saarbrücken, Germany.

Yang, K.-H., Jung, Y.-B., Cho, M.-S., Tae, S.-H., 2015. Effect of supplementary cementitious materials on reduction of CO2 emissions from concrete. Journal of Cleaner Production 103, 774-783.

Yi, I., Itsubo, N., Inaba, A., Matsumoto, K., 2007. Development of the interregional I/O based LCA method considering region-specifics of indirect effects in regional evaluation. The International Journal of Life Cycle Assessment 12(6), 353.

Zhao, S., Huang, B., Shu, X., Jia, X., Woods, M., 2012. Laboratory Performance Evaluation of Warm-Mix Asphalt Containing High Percentages of Reclaimed Asphalt Pavement. Transportation Research Record 2294(1), 98-105.

Zhao, S., Huang, B., Shu, X., Woods, M., 2013. Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement. Construction and Building Materials 44, 92-100.

Table A.1 Regional and alternate distribution of LCA studies on pavements and other roadworks

Case study region	Study references based on the three recent state-of-the-art reviews on LCAs of pavement sections and associated roadworks		
	Hasan et al. (2019)	**AzariJafari et al. (2016)**	**Balaguera et al. (2018)**
Asia	Chen et al. (2017)		Chiu et al. (2008)
Europe	Moretti et al. (2018); Celauro et al. (2017); Karlsson et al. (2017); Butt and Birgisson (2016); Butt et al. (2016); Turk et al. (2016); Anastasiou et al. (2015); Santos et al. (2015a); Du et al. (2014)	Celauro et al. (2015);Santos et al. (2015b); Vidal et al. (2013)	Vidal et al. (2013); Araújo et al. (2014); Olsson et al. (2006); Birgisdottir et al. (2006); Butt (2014); Birgisdottir et al. (2007); Huang et al. (2009); Ferreira et al. (2016)
Middle East	Hadi et al. (2013)		
Oceania	Biswas (2014)		
Americas	Bloom et al. (2017);Choi et al. (2015);Yu and Lu (2014);Yu and Lu (2012);Wang et al. (2012); Cass and Mukherjee (2011); Lee et al. (2010)	Liu et al. (2015); Aurangzeb et al. (2014); Noshadravan et al. (2013); Zhang et al. (2010); Qian et al. (2013); Wang et al. (2012); Santos et al. (2015a); Chen et al. (2016); Reza et al. (2014)	Eleanor et al. (2016); Aurangzeb et al. (2014); Kucukvar and Tatari (2012); Yu and Lu (2012); Wang et al. (2012); Yu et al. (2013); Thenoux et al. (2007)
Recycled construction waste aggregates (RCW)	Bloom et al. (2017); Celauro et al. (2017); Anastasiou et al. (2015); Biswas (2014); Turk et al. (2016)	Wang et al. (2012)	Yu and Lu (2012); Del Ponte (2016); Eleanor et al. (2016); Ferreira et al. (2016)
Warm-mix asphalt (WMA)	Butt and Birgisson (2016)	Vidal et al. (2013)	
Streetlights & concrete works	Hadi et al. (2013)		
Recycled asphalt pavement (RAP)	Bloom et al. (2017); Celauro et al. (2017); Turk et al. (2016); Anastasiou et al. (2015); Biswas (2014)	Aurangzeb et al. (2014); Vidal et al. (2013); Santos et al. (2015a)	Bloom et al. (2017); Del Ponte (2016); Celauro et al. (2015); Thenoux et al. (2007); Chiu et al. (2008); Huang et al. (2009); Vidal et al. (2013); Araújo et al. (2014); Aurangzeb et al. (2014)
Other materials	Chen et al. (2017); Choi et al. (2015); Liu et al. (2014); Yu and Lu (2012); Lee et al. (2010)	Qian et al. (2013); Zhang et al. (2010)	Araújo et al. (2014); Chiu et al. (2008); Ferreira et al. (2016); Olsson et al. (2006); Birgisdottir et al. (2007); Huang et al. (2009)
Embankments & earthworks	Moretti et al. (2018)		

Table A.2 LCI of synthetic zeolite production used as the additive for production of warm-mix asphalt

Material inventory (***based on Fawer et al. (1998)***)	**Material quantity (per tonne of zeolite)** (***based on Fawer et al. (1998)***)
Inputs	
Bauxite	762 kg/tonne
Sand	467 kg/tonne
Rock salt	222 kg/tonne
Limestone	40 kg/tonne
Washed sand	467 kg/tonne
Sodium hydroxide 100 (50%-aq.)	336 kg/tonne
Sodium-silicate $Na_2O + 2SiO_2$	636 kg/tonne
Aluminium hydroxide ($Al(OH)_3$)	606 kg/tonne
Water for steam production	1.5 m^3/tonne
Cleaning agent	1.7 kg/tonne
Filter clothes	0.08 kg/tonne
Water conditioner	0.07 kg/tonne
Stabilisers (tensides)	30.6 kg/tonne
Compressed air	64.7 Nm^3/tonne
Electricity consumption	8,537 MJ/tonne
Coal consumption	508 MJ/tonne
Heavy oil consumption	4,561 MJ/tonne
Average/light oil consumption	749 MJ/tonne
Diesel oil consumption	593 MJ/tonne
Others	94 MJ/tonne
Natural gas consumption	11,419 MJ/tonne

Table A.3 Detailed Monte Carlo uncertainty assessment results for pavement works, "baseline case" against "alternate materials case"

Impact category	**A < B***	**A ≥ B****
Global warming	0%	100%
Stratospheric ozone depletion	0%	100%
Ionizing radiation	0%	100%
Ozone formation, Human health	0%	100%
Fine particulate matter formation	0%	100%
Ozone formation, Terrestrial ecosystems	0%	100%
Terrestrial acidification	0%	100%
Freshwater eutrophication	0%	100%
Marine eutrophication	0%	100%
Terrestrial ecotoxicity	0%	100%
Freshwater ecotoxicity	1.3%	98.7%
Marine ecotoxicity	0.6%	99.4%
Human carcinogenic toxicity	0.2%	99.8%
Human non-carcinogenic toxicity	2.2%	97.8%
Land use	0%	100%
Mineral resource scarcity	10.9%	89.1%
Fossil resource scarcity	0%	100%
Water consumption	48.5%	51.5%

** Number of cases from Monte Carlo simulation where the environmental impacts from "**Baseline case pavement works (A)**" is less than the environmental impacts from "**Alternate materials pavement works case (B)**".*

*** Number of cases from Monte Carlo simulation where the environmental impacts from "**Baseline case pavement works (A)**" is greater than or equal to the environmental impacts from "**Alternate materials pavement works case (B)**".*

1. References

Anastasiou, E.K., Liapis, A., Papayianni, I., 2015. Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. Resources, Conservation and Recycling 101, 1-8.

Araújo, J.P.C., Oliveira, J.R., Silva, H.M., 2014. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transportation Research Part D: Transport and Environment 32, 97-110.

Aurangzeb, Q., Al-Qadi, I.L., Ozer, H., Yang, R., 2014. Hybrid life cycle assessment for asphalt mixtures with high RAP content. Resources, Conservation and Recycling 83, 77-86.

AzariJafari, H., Yahia, A., Ben Amor, M., 2016. Life cycle assessment of pavements: reviewing research challenges and opportunities. Journal of Cleaner Production 112, 2187-2197.

Balaguera, A., Carvajal, G.I., Albertí, J., Fullana-i-Palmer, P., 2018. Life cycle assessment of road construction alternative materials: A literature review. Resources, Conservation and Recycling 132, 37-48.

Birgisdottir, H., Bhander, G., Hauschild, M.Z., Christensen, T.H., 2007. Life cycle assessment of disposal of residues from municipal solid waste incineration: recycling of bottom ash in road construction or landfilling in Denmark evaluated in the ROAD-RES model. Waste Management 27(8), S75-S84.

Birgisdottir, H., Pihl, K., Bhander, G., Hauschild, M.Z., Christensen, T.H., 2006. Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration. Transportation Research Part D: Transport and Environment 11(5), 358-368.

Biswas, W.K., 2014. Carbon footprint and embodied energy assessment of a civil works program in a residential estate of Western Australia. The International Journal of Life Cycle Assessment 19(4), 732-744.

Bloom, E., Canton, A., Ahlman, A.P., Edil, T., 2017. Life Cycle Assessment of Highway Reconstruction: A Case Study, Transportation Research Board 96th Annual Meeting. Transportation Research Board, Washington DC, United States, p. 19.

Butt, A.A., 2014. Life Cycle Assessment of Asphalt Roads: Decision Support at the Project Level. KTH Royal Institute of Technology.

Butt, A.A., Birgisson, B., 2016. Assessment of the attributes based life cycle assessment framework for road projects. Structure and Infrastructure Engineering 12(9), 1177-1184.

Butt, A.A., Birgisson, B., Kringos, N., 2016. Considering the benefits of asphalt modification using a new technical life cycle assessment framework. Journal of Civil Engineering and Management 22(5), 597-607.

Cass, D., Mukherjee, A., 2011. Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: case study for pavement operations. Journal of Construction Engineering and Management 137(11), 1015-1025.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., 2015. Environmentally appraising different pavement and construction scenarios: A comparative analysis for a typical local road. Transportation Research Part D: Transport and Environment 34, 41-51.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., Rizzo, A., 2017. Environmental analysis of different construction techniques and maintenance activities for a typical local road. Journal of Cleaner Production 142, 3482-3489.

Chen, F., Zhu, H., Yu, B., Wang, H., 2016. Environmental burdens of regular and long-term pavement designs: a life cycle view. International Journal of Pavement Engineering 17(4), 300-313.

Chen, J., Zhao, F., Liu, Z., Ou, X., Hao, H., 2017. Greenhouse gas emissions from road construction in China: A province-level analysis. Journal of Cleaner Production 168, 1039-1047.

Chiu, C.-T., Hsu, T.-H., Yang, W.-F., 2008. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. Resources, Conservation and Recycling 52(3), 545-556.

Choi, K., Lee, H., Mao, Z., Lavy, S., Ryoo, B., 2015. Environmental, Economic, and Social Implications of Highway Concrete Rehabilitation Alternatives. Journal of Construction Engineering and Management 142(2), 04015079.

Del Ponte, K.L., 2016. State DOT environmental and economic benefits of recycled material utilization in highway pavements, Geological Engineering. University of Wisconsin–Madison, Madison, Wisconsin, p. 158.

Du, G., Safi, M., Pettersson, L., Karoumi, R., 2014. Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. The International Journal of Life Cycle Assessment 19(12), 1948-1964.

Eleanor, B.F., Gregory, H.J., Angela, A.P., Tuncer, E.B., Whited, G., 2016. Assessing the life cycle benefits of recycled material in road construction, in: Zekkos, D., Farid, A., De, A., Reddy, K.R., Yesiller, N. (Eds.), Geo-Chicago 2016: Sustainability and Resiliency in Geotechnical Engineering. American Society of Civil Engineers, Chicago, Illinois, pp. 613-622.

Fawer, M., Postlethwaite, D., Klüppel, H.J., 1998. Life cycle inventory for the production of zeolite a for detergents. The International Journal of Life Cycle Assessment 3(2), 71-74.

Ferreira, V.J., Sáez-De-Guinoa Vilaplana, A., García-Armingol, T., Aranda-Usón, A., Lausín-González, C., López-Sabirón, A.M., Ferreira, G., 2016. Evaluation of the steel slag incorporation as coarse aggregate for road construction: technical requirements and environmental impact assessment. Journal of Cleaner Production 130, 175-186.

Hadi, S.A., Al Kaabi, M.R., Al Ali, M.O., Arafat, H.A., 2013. Comparative life cycle assessment (LCA) of streetlight technologies for minor roads in United Arab Emirates. Energy for Sustainable Development 17(5), 438-450.

Hasan, U., Whyte, A., Al Jassmi, H., 2019. Critical review and methodological issues in integrated life-cycle analysis on road networks. Journal of Cleaner Production 206, 541-558.

Huang, Y., Bird, R., Heidrich, O., 2009. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. Journal of Cleaner Production 17(2), 283-296.

Karlsson, C.S.J., Miliutenko, S., Björklund, A., Mörtberg, U., Olofsson, B., Toller, S., 2017. Life cycle assessment in road infrastructure planning using spatial geological data. The International Journal of Life Cycle Assessment 22(8), 1302-1317.

Kucukvar, M., Tatari, O., 2012. Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements. Transportation Research Part D: Transport and Environment 17(1), 86-90.

Lee, J., Edil, T., Tinjum, J., Benson, C., 2010. Quantitative assessment of environmental and economic benefits of recycled materials in highway construction. Transportation Research Record: Journal of the Transportation Research Board(2158), 138-142.

Liu, R., Liu, Y., Ji, B., Wang, M., Tian, Y., 2014. Hot spot stress analysis on rib–deck welded joint in orthotropic steel decks. Journal of Constructional Steel Research 97, 1-9.

Liu, R., Smartz, B.W., Descheneaux, B., 2015. LCCA and environmental LCA for highway pavement selection in Colorado. International Journal of Sustainable Engineering 8(2), 102-110.

Moretti, L., Mandrone, V., D'Andrea, A., Caro, S., 2018. Evaluation of the environmental and human health impact of road construction activities. Journal of Cleaner Production 172, 1004-1013.

Noshadravan, A., Wildnauer, M., Gregory, J., Kirchain, R., 2013. Comparative pavement life cycle assessment with parameter uncertainty. Transportation Research Part D: Transport and Environment 25, 131-138.

Olsson, S., Kärrman, E., Gustafsson, J.P., 2006. Environmental systems analysis of the use of bottom ash from incineration of municipal waste for road construction. Resources, Conservation and Recycling 48(1), 26-40.

Qian, S.Z., Li, V.C., Zhang, H., Keoleian, G.A., 2013. Life cycle analysis of pavement overlays made with Engineered Cementitious Composites. Cement and Concrete Composites 35(1), 78-88.

Reza, B., Sadiq, R., Hewage, K., 2014. Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: a case study on paved roads. Clean Technologies and Environmental Policy 16(2), 251-266.

Santos, J., Bryce, J., Flintsch, G., Ferreira, A., Diefenderfer, B., 2015a. A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. Structure and Infrastructure Engineering 11(9), 1199-1217.

Santos, J., Ferreira, A., Flintsch, G., 2015b. A life cycle assessment model for pavement management: road pavement construction and management in Portugal. International Journal of Pavement Engineering 16(4), 315-336.

Thenoux, G., González, Á., Dowling, R., 2007. Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. Resources, Conservation and Recycling 49(4), 325-339.

Turk, J., Mauko Pranjić, A., Mladenovič, A., Cotič, Z., Jurjavčič, P., 2016. Environmental comparison of two alternative road pavement rehabilitation techniques: cold-in-place-recycling versus traditional reconstruction. Journal of Cleaner Production 121, 45-55.

Vidal, R., Moliner, E., Martínez, G., Rubio, M.C., 2013. Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. Resources, Conservation and Recycling 74, 101-114.

Wang, T., Lee, I.-S., Kendall, A., Harvey, J., Lee, E.-B., Kim, C., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. Journal of Cleaner Production 33, 86-96.

Yu, B., Lu, Q., 2012. Life cycle assessment of pavement: Methodology and case study. Transportation Research Part D: Transport and Environment 17(5), 380-388.

Yu, B., Lu, Q., 2014. Estimation of albedo effect in pavement life cycle assessment. Journal of Cleaner Production 64, 306-309.

Yu, B., Lu, Q., Xu, J., 2013. An improved pavement maintenance optimization methodology: Integrating LCA and LCCA. Transportation Research Part A: Policy and Practice 55, 1-11.

Zhang, H., Lepech Michael, D., Keoleian Gregory, A., Qian, S., Li Victor, C., 2010. Dynamic Life-Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration. Journal of Infrastructure Systems 16(4), 299-309.