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Using different performance measures for the sustainability assessment of asphalt mixtures: case of warm mix asphalt in a hot climate

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The study presents a framework for assessing the sustainability of different types of asphalt materials and technologies. The framework is demonstrated through a case study for evaluating the sustainability of warm mix asphalt (WMA) mixtures in hot climatic conditions. While various life-cycle assessment (LCA) tools and methodologies have been used for sustainability assessment of WMA from the material production phase to the construction phase, most neglect the maintenance, rehabilitation and end of life phases, based on the assumption that the performance of WMA is similar to that of hot mix asphalt (HMA). This study examines asphalt mix properties and performance indices, and studies their impact on maintenance and rehabilitation schedules when incorporated in a pavement structure, and subsequently life-cycle environmental and economic costs. The study concludes that the assessment outcomes of the LCA and life-cycle cost analysis are heavily affected by the performance measure used to predict the maintenance and rehabilitation schedule or change in service life. For the conditions assumed in the study, WMA mixes yield more favourable environmental and economic results compared to control HMA mixes with unmodified binder.

Keywords: life-cycle assessment; warm mix asphalt; life-cycle cost analysis; sustainability assessment; performance assessment; asphalt pavement

Introduction

A sustainable pavement has been best defined as one that achieves its specific engineering goals in terms of adequate material and structural performance while, on a broader scale, (1) meets basic human needs, (2) uses resources effectively, and (3) preserves/restores surrounding ecosystems (Al Hassanieh, Kassem, Chehab, & Abiad, 2015; Harvey et al., 2016; Muench & Van Dam, 2014; Van Dam et al., 2015). Measuring pavement sustainability is thus essential in order to quantify, manage, or improve current pavement practices as well as emerging technologies. Three main measurement methods can be used to quantify various aspects of sustainability (Muench & Van Dam, 2014): (1) performance assessment, which entails assessing the overall pavement performance in relation to its intended function, (2) life-cycle assessment (LCA), which entails analysing and quantifying environmental impacts of the pavement over its life cycle, and (3) life-cycle cost analysis (LCCA), which entails evaluating the total cost of the pavement over its life cycle. Although the ISO guidelines for sustainability assessment apply to pavement structures

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and systems in a general sense (ISO 14040, 2006), sustainability is context sensitive; therefore, the methods used to quantify pavement sustainability are unique for each pavement application.

The purpose of this study is to present a general framework for assessing the sustainability of different types of asphalt materials and technologies. The framework is applied through a case study to evaluate the sustainability of warm mix asphalt (WMA) mixtures in hot climatic conditions. WMA can be produced using a variety of commercial products, such as wax-based organic additives, chemical additives, and water-based technologies, to reduce the production temperature of the asphalt mix by reducing viscosity of the asphalt binder (Chowdhury & Button, 2008; D'Angelo et al., 2008). Research studies have shown that adopting WMA technologies can result in reductions in energy consumption and emissions associated with mixture production while improving performance through improved aggregate coating and compaction efficiency, among other factors (Button, Estakhri, & Wimsatt, 2007; Chowdhury & Button, 2008; D'Angelo et al., 2008; Kassem, Chehab, & Saad, 2015; Rubio, Martínez, Baena, & Moreno, 2012). Research conducted on WMA, however, has mostly focused on its use in cold or moderate climatic regions. Multiple studies reported reductions in CO_2 emissions ranging from 15% to 46%, and reductions in energy consumption ranging from 20% to 70% during the asphalt mix production phase (Rubio et al., 2012). Additionally, numerous studies have investigated the moisture sensitivity of WMA (Alavi, Hajj, Hanz, & Bahia, 2012; Buss, Williams, & Schram, 2016; Martin, Arambula, Yin, & Park, 2016) and its susceptibility to cracking (Das, Tasdemir, & Birgisson, 2012; Haggag, Mogawer, & Bonaquist, 2011; Sadeq, Masad, Al-Khalid, & Sirin, 2015). The investigation of the sustainability performance of WMA when subjected to compressive stresses, however, is yet to be sufficiently researched.

Another gap in past research on WMA is manifested in the lack of effective incorporation of the maintenance and rehabilitation activities as well as the end-of-life phase when conducting LCA studies. It is common among such studies to address the life-cycle phases of material production and construction, but neglect the later phases of the pavement service life (Hassan, 2010; Rodríguez-Alloza, Malik, Lenzen, & Gallego, 2015; Wu & Qian, 2014).

Building on the aforementioned discussion, the main aim of the research presented herein narrows down to investigate whether the adoption of WMA in climatic conditions that favour asphalt rutting is a sustainability best practice, by examining asphalt mix performance, and its impact on life-cycle environmental and economic burdens. Sustainability best practices are defined as activities that result in reductions in any or all of (1) the quantities of nonrenewable resources consumed either as fuel or as direct materials, (2) the amount of greenhouse gas (GHG) emissions generated, and (3) the associated ecological impacts (Harvey et al., 2016; Muench & Van Dam, 2014; Van Dam et al., 2015).

Study scope

Three measurement methodologies are adopted for sustainability assessment of WMA mixtures:

(1) performance assessment, based on two different material characterisation models: (a) linear viscoelastic (LVE) model, and (b) viscoelastic continuum damage (VECD) model;
(2) LCA, using the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (Horvath, 2004); and
(3) LCCA, using net present value (NPV) calculations.

Eight asphalt mixes (Table 1) are utilised in this study. These mixes are produced using two binders: an unmodified (neat) binder (PG 64-22) and a polymer-modified binder (PG 76-22), and

Table 1. Mix designations of asphalt mixes included in scope.

NMAS (mm)	Binder Grade	WMA Additive	Mix Designation
19	Polymer-**M**odified Binder (PG 76-22)	–	**19M-H***
		Foaming	19M-W-F
		Chemical	19M-W-C
		Organic (wax)	19M-W-O
25	**U**nmodified Binder (PG 64-22)	–	**25U-H***
		Foaming	25U-W-F
		Chemical	25U-W-C
		Organic (wax)	25U-W-O

*Control HMA mix.

three WMA technologies: chemical, foaming-based, and organic (wax) additives. All asphalt mixes are fabricated using Gabbro aggregates following two gradations: the first with a nominal maximum aggregate size (NMAS) of 19 mm and the other 25 mm. Gradations are designed to pass the Superpave Criteria and the Bailey Conformity Equations in order to ensure effective packing and interlock of aggregates in the aim of providing strong resistance to rutting (Vavrik, Pine, & Carpenter, 2002). All mixes are designed for a target air void content (%AV) of 4.0%.

The eight mixes are categorised into two groups based on the combination of aggregate gradation and binder type. Each group comprises of an hot mix asphalt (HMA) mix and three corresponding WMA mixes as shown in Table 1. The WMA mixes are designed using the same optimum asphalt content as that of their corresponding HMA control mix, and using WMA additive dosages as per ranges recommended by the suppliers. For the sake of consistency and comparison, the same reduction in mixing and compaction temperatures of 20°C for modified (PG 76-22) and 35°C for unmodified (PG 64-22) WMA mixes is implemented, regardless of the type of additive and without changing the asphalt content. Only dosages of the additives were changed to ensure consistent reduction in fabrication temperatures. The mix designs of the asphalt mixes are detailed in Table 2. Note that WMA mixes with PG 76-22 binder require a higher dosage of additives than those with PG 64-22 despite the smaller reduction in the mixing and compaction temperatures.

The climatic profile of Doha, Qatar, is chosen to represent hot climatic regions. Doha offers a typical representation of the climate in the Gulf Cooperative Council (GCC) countries, and is similar to the hot climates witnessed in some international cities, such as Phoenix (USA), Las Palmas (Spain), Alice Springs (Australia), Upington (South Africa), Lima (Peru), among others.

Framework for sustainability assessment of asphalt mixes

As outlined in the study scope, three main sustainability measurement methods are used to assess the sustainability of WMA in climatic conditions that favour asphalt rutting: (1) performance assessment, (2) LCA, and (3) LCCA. The framework for the sustainability analysis consists of four main stages, as shown in Figure 1 and as explained below:

- *Stage I: Mix characterisation*: Asphalt material characterisation is conducted at two levels: (1) using LVE response functions (no damage), and (2) using a VECD model. LVE response functions and the VECD material model provide fundamental material properties that are predictors of performance and appear in primary prediction relationships; i.e. models that can be used to predict pavement distresses from combinations of design

Table 2. Mix designs of asphalt mixes included in scope.

		19M-H	19M-W-F	19M-W-C	19M-W-O	25U-H	25U-W-F	25U-W-C	25U-W-O
Binder content, % (by weight of mix)		3.9	3.9	3.9	3.9	3.6	3.6	3.5	3.5
G_{mm}		2.689	2.687	2.669	2.688	2.716	2.717	2.718	2.718
VIM (%)		4.0	4.0	4.0	4.0	4.0	3.9	4.0	4.0
VMA (%)		14.0	14.0	14.5	14.0	12.4	12.4	12.4	12.3
VFB (%)		71.4	71.4	72.4	71.4	67.7	68.5	67.7	67.5
PG binder		PG 76-10 V	PG 76-10 V	PG 76-10 V	PG 76-10 V	PG 64-22	PG 64-22	PG 64-22	PG 64-22
WMA additive (kg/ton)		N/A	2.5	0.195	1.17	N/A	1	0.175	0.35
Mixing temp. (°C)		160	140	140	140	160	125	125	125
Compaction temp. (°C)		150	130	130	130	150	115	115	115
Aggregate type		Gabbro							
NMAS, mm		**19**				**25**			
% Passing	3/4″	96.0				82.0			
	3/8″	69.0				66.0			
	No. 4	48.0				50.0			
	No. 200	4.2				4.5			

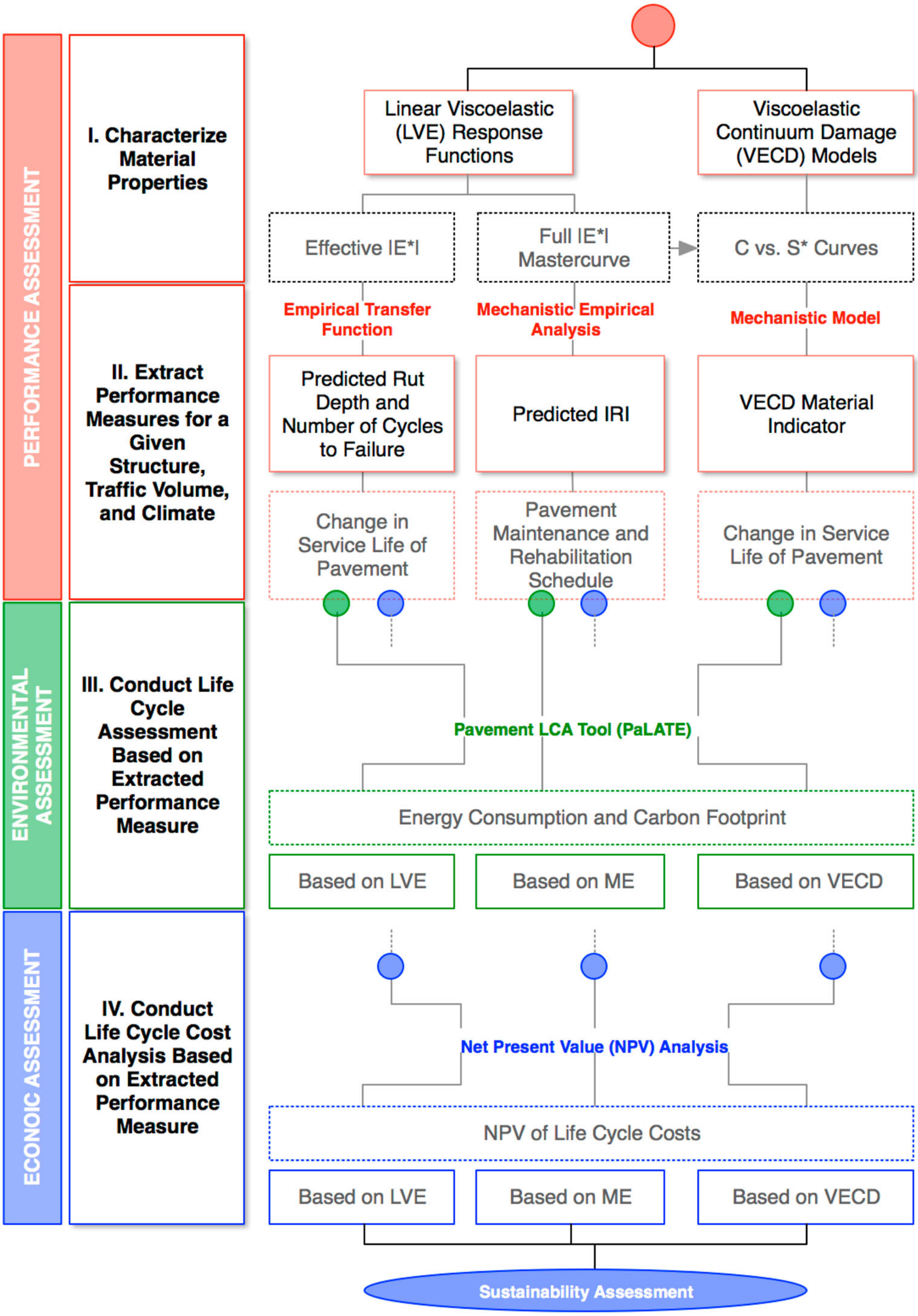


Figure 1. Framework for the sustainability assessment of asphalt mixes using different performance measures.

parameters: traffic, material properties, environmental, roadbed, and structural conditions (Daniel, Chehab, & Ayyala, 2009; Leahy, 2009).

- *Stage II: Performance measures*: Three different performance measures are extracted based on the material characterisation of mixes described above to acquire the change in service life or the maintenance and rehabilitation schedule for each mix:
  1. predicted rut depth and number of cycles to failure using an empirical transfer function based on LVE response functions, namely, effective $|E^*|$, as defined in the following sections;
  2. predicted distresses based on mechanistic-empirical (ME) analysis using full $|E^*|$ mastercurve; and
  3. VECD material indicator, calculated as the ratio of predicted viscoelastic strain resulting from a given stress input and temperature for WMA mix to that of its reference HMA mix.

Note that pavement performance has a direct and main influence on the service life of a pavement, as well as the maintenance and rehabilitation phase of a pavement's life cycle, and therefore, significantly impacts the results of LCA and LCCA (Hamdar, Chehab, & Srour, 2016).

- *Stage III: LCA*: The change in service life or the maintenance and rehabilitation schedule for each mix is incorporated in the LCA to account for the performance of each of the mixes. This is done for the three performance measures acquired in Stage II. The LCA focuses on changes in energy consumption and global warming potential (GWP) with the use of the various WMA technologies as compared to control HMA.
- *Stage IV: LCCA*: Similar to the LCA, the LCCA incorporates the performance of each of the mixes through the service life of the pavement or the maintenance and rehabilitation schedule based on the performance measures acquired in Stage II.

Methodology used to apply the various stages of the framework

This section describes the methodology used to conduct each stage of the framework described in the previous section and summarised in Figure 1.

Characterising asphalt material properties

Material characterisation of the asphalt mixes is done at two levels: (1) using LVE characterisation, and (2) using a VECD modelling, as described below.

LVE characterisation

The complex modulus test (E^*) is conducted in the stress control mode to determine the LVE properties and the time–temperature shift factors of all mixes each of the eight mixes included in the scope. The test is conducted using a universal testing machine (UTM-25) by applying a uniaxial sinusoidal stress to an unconfined AC sample to determine its response strain. For each mix, 3 replicates are tested at 24 combinations of temperature and frequency. The average $|E^*|$ mastercurve for each mix is constructed at a reference temperature of 20°C and is presented in Figure 2. In addition to plotting the mastercurves, the effective $|E^*|$ for rutting is calculated for each of the mixes, based on a traffic speed of 60 mph and the climate of Doha: mean annual air temperature (MAAT) of 27.6°C [82°F], mean annual monthly temperature standard deviation (σ_{MAMT}) of 7.4°C, mean wind speed of 14.5 km/h [9 mph], per cent sunshine of 68%, and annual

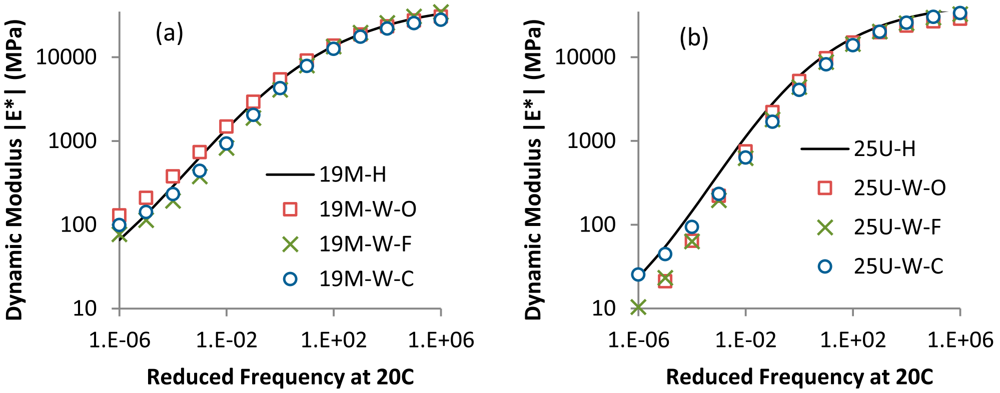


Figure 2. Dynamic modulus mastercurves of HMA and WMA mixes with: (a) PG 64-22 binder and 25 mm NMAS, and (b) PG 76-22 binder and 19 mm NMAS.

Table 3. Rut depth and change in service life based on effective $|E^*|$.

Mix	Effective $\|E^*\|$ for rutting (E_i) (MPa) [ksi]	No of cycles to failure (ESAL$_i$)*	Year of major rehab, assuming 20-year service Life	% Change in service life compared to HMA
19M-H	**2228 [323]**	**8,567,850**	**17**	–
19M-W-F	1565 [227]	7,671,637	15.5	− 10.5
19M-W-C	1720 [249]	7,901,989	16	− 7.8
19M-W-O	2499 [362]	8,881,448	18	+ 3.7
25U-H	**1967 [285]**	**8,240,754**	**16**	–
25U-W-F	1664 [241]	7,819,781	15.5	− 5.1
25U-W-C	2275 [330]	8,624,326	17	+ 4.7
25U-W-O	3116 [452]	9,516,688	19	+ 15.5

*Assuming failure of pavement in asphalt rutting is 0.64 cm [0.25 in].

cumulative rainfall depth of 7 cm [2.7 in]. Although full hourly or daily climate characterisation is required for advanced ME analysis, these average values of climatic inputs offer a general representation of the climatic profile of the city, and are the inputs required to calculate the effective temperature and subsequently the effective $|E^*|$ (El-Basyouny & Jeong, 2010a). The effective $|E^*|$ is defined as the representative $|E^*|$ value of the mix which corresponds to a specific combination of frequency and temperature that is prevalent for the pavement under design. The larger the value of effective $|E^*|$, the better the rutting performance of the mix (Hamdar, Kassem, Srour, & Chehab, 2015). The formulas for calculating the effective $|E^*|$ can be found in (El-Basyouny & Jeong, 2010a, 2010b; Hamdar & Chehab, 2017; Witczak & Uzan, 2011). The effective $|E^*|$ values for the mixes included in the scope, under the above-stated conditions, are provided in Table 3. By comparing the effective $|E^*|$ values, it is observed that, for the materials used, WMA additives have a more favourable effect on the rutting resistance of unmodified mixes than modified mixes. It appears that WMA additives improve the rate of change of stiffness as a function reduced frequency for the unmodified mixes (Figure 2).

VECD modelling

A VECD model is used to assess the rate-dependent behaviour of WMA mixes compared to HMA under rut-inducing compressive loading. Several studies have shown that the VECD model is capable of accurately predicting the stress–strain behaviour of HMA mixes under different conditions (Chehab, Kim, Schapery, Witczak, & Bonaquist, 2003; Underwood, Yun, & Kim, 2010; Yun & Richard Kim, 2013; Zhao, 2002). The VECD modelling approach selected for this study is based on Schapery's continuum damage model (Chehab et al., 2003; Chehab, Kim, Schapery, Witczak, & Bonaquist, 2002; Schapery, 1984). For each of the mixes, the constant crosshead rate tests are conducted using the UTM-25 at 5°C and yielded damage characteristic curves (C vs. S curves) that collapse on top of each other, indicating minimal presence of viscoplasticity, if any. The pseudostiffness, C, represents the change in the stiffness of the asphalt mixture due to microstructure damage, and ranges between 1 for virgin material and 0 for complete failure. S is a global damage parameter defined as the Lebesgue norm of pseudostrain, which is a function obtained from corresponding time and strain of the test. More on C and S is provided in Chehab (2002). The viscoelastic model for all mixes are developed based on the outputs of tests conducted at 5°C and rates of 0.0001 and 0.00005 strain/s. For each mix, the third replicate, tested at 0.000025 strain/s, is used for validation. The predicted viscoelastic strains fit perfectly with the on-specimen measured strains, showing that the developed models are accurate. The C vs. S curves are plotted in Figure 3. A test temperature of 5°C is selected to ensure the behaviour is viscoelastic with minimal or no viscoplasticity. Additional crosshead tests conducted at 35°C showed that viscoplastic strain contributes to 25–35% of total damage. To simplify the analysis, viscoplasticity is not addressed in the study but is examined in a separate study by the authors (Kassem, 2017).

Performance measures to be used in LCA and LCCA

Three performance measures are devised to compare the performance of the mixes. These measures are later used to predict maintenance and rehabilitation schedules or change in service life for LCA and LCCA. As depicted in Figure 1, the three performance measures are:

1. predicted rut depth and number of cycles to failure acquired using empirical transfer function based on effective $|E^*|$;
2. predicted distresses based on ME analysis using full $|E^*|$ mastercurve (Level 1 asphalt material properties); and
3. material performance indicator based on VECD material model.

The methodologies used to acquire these three performance measures are described below.

Predicted rut depth and number of cycles to failure based on effective $|E^*|$

Asphalt rut depth at the end of the service life for each mix is estimated using the following calibrated model (Jeong, 2010):

$$\text{Rut Depth} = 2.73(1.45 \times E^*_{\text{eff}})^{-0.85},$$

where rut depth is expressed in cm, and E^*_{eff} in (10^{-3}) MPa. The asphalt rut depth, in this equation, corresponds to a pavement section in a hot climate, consisting of 20 cm [7.8 in] thick asphalt concrete layer, a 35 cm [13.8 in] granular base layer and a subgrade of a resilient modulus of 100 MPa [14.5 ksi], and subjected to a traffic volume of 10 million equivalent single axle loads (ESALs). The asphalt rut depths, based on the aforementioned equation, corresponding to the mixes included in the scope are specified in Table 3.

The failure limit for asphalt rutting is set at 0.64 cm [0.25 in], as per guidelines in the Mechanistic Empirical Pavement Design Guide (Witczak, Andrei, & Houston, 2004). A rut depth of

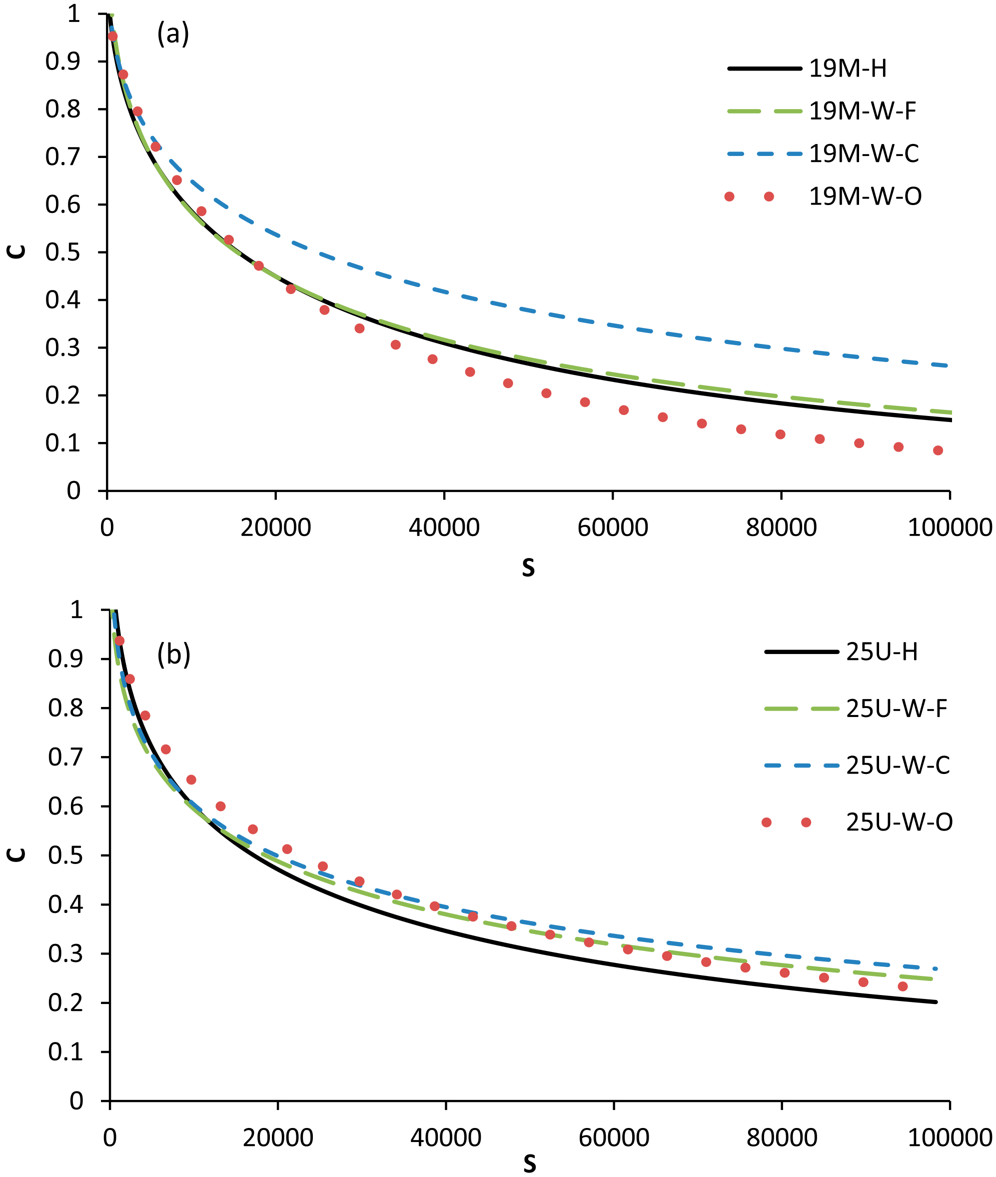


Figure 3. Damage characteristic curves for HMA and WMA mixes with: (a) PG76-22 binder and 25 mm NMAS, and (b) PG64-22 binder and 19 mm NMAs.

0.64 cm [0.25 in], in this case, is associated with 10 Million ESALs and an $|E^*|$ of 3650 MPa [529 ksi]. To acquire the change in service life, the number of cycles to failure for each mix is back-calculated on the basis that rut depth is proportional to $N^{0.479}$, and using the following equation (Witczak, El-Basyouny, & Uzan, 2011):

$$\frac{\text{Rut}_i}{\text{Rut}_c} = \frac{(\text{ESAL}_i^{0.479})(E_c)}{(\text{ESAL}_c^{0.479})(E_i)},$$

where ESAL_i is the total number of traffic repetitions causing Rut_i in a certain period; ESAL_c is the total number of traffic repetitions (10 million ESALs) causing Rut_c in design period (0.64 cm); E_i is the [effective] dynamic modulus associated with Rut_i, and E_c is the [effective] dynamic modulus associated with Rut_c (3650 MPa). The ratio of Rut_i to Rut_c is set at a value of 'one'. The time of major rehabilitation (in year) is calculated based on the following formula, assuming a service life of 20 years and no traffic growth:

$$\text{Year of Major Rehab} = \frac{\mathrm{ESAL}_i}{\mathrm{ESAL}_c} \times 20 \text{ years.}$$

The number of cycles to failure, the corresponding time of major rehabilitation, and per cent change in service life are reported in Table 3.

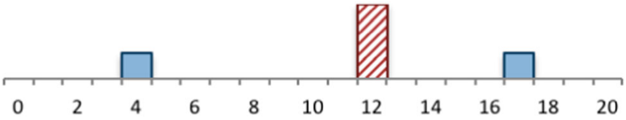
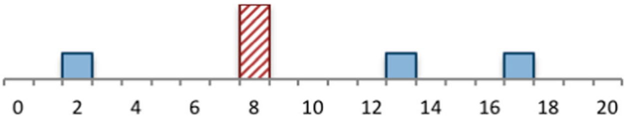
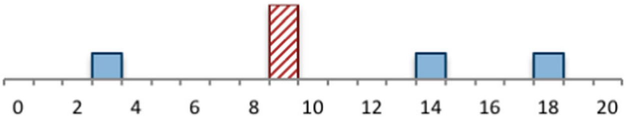
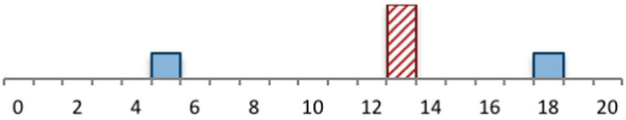
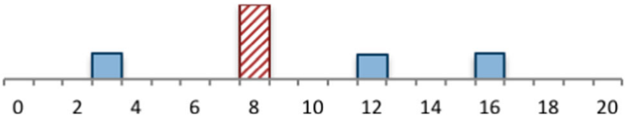
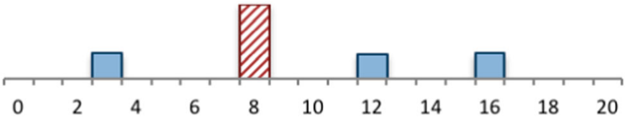
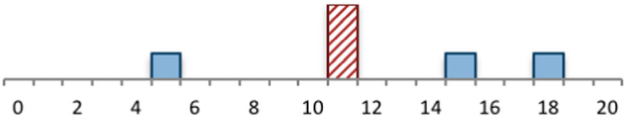
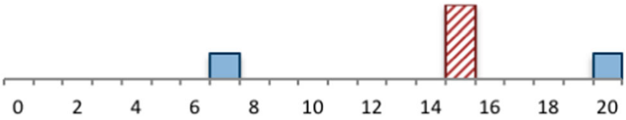
Predicted distresses based on ME analysis

ME analysis utilises the full $|E^*|$ mastercurve and offers the opportunity of incorporating scenario-specific inputs (traffic characteristics, climate, material properties, and structure), and performance prediction. In order to closely reflect actual design scenarios, design thicknesses are acquired using Pavement-ME (Version 2.3.1), with Level 1 material input data for asphalt mixes and for a traffic level of 15,000 average annual daily truck traffic (AADTT), failure criterion of 30% fatigue cracking at 20 years, and for the climate of Needles, California which is an adequate representation of the climate of Doha (Sadek et al., 2014). The design thicknesses, reported in Table 4, are used to quantify the difference in material quantities required for each mix type. IRI (international roughness index) profiles generated by Pavement-ME reflect the predicted pavement distresses, namely rutting and fatigue cracking. Therefore, IRI profiles at 90% reliability are used to determine the pavement maintenance schedule corresponding to each asphalt mix. To simplify the development of the maintenance schedule, chip seal treatment is selected as the maintenance activity, assuming 2 l/m^2 [0.05 gal/ft^2] emulsion and 20 kg/m^2 [4 lb/ft^2] aggregate application, and a 5 cm [2 in] functional HMA overlay with polymer-modified binder is selected as the rehabilitation activity. The trigger for the overlay is considered to be an IRI value of 2.0 m/km [125 in/mi]. The trigger for chip seal is considered to be an IRI value of 1.8 m/km [115 in/mi] if the treatment is to be done before overlay, and 1.7 m/km [110 in/mi] if the treatment is to be done after. For simplicity, it is assumed that only asphalt overlay would have a major impact on IRI, and the IRI after rehabilitation drops to the original IRI value at initial construction. The validity of this assumption, however, requires further study in the future. The IRI curves of pavements with the different mix types after rehabilitation are shown in Figure 4 and the corresponding maintenance and rehabilitation schedules are presented in Table 4.

VECD material indicator

To predict the response for a given loading history considering both the LVE properties and damage characteristics, 300 creep and recovery cycles are used with a loading and rest period of 0.1 and 0.9 s, respectively, and an applied compressive stress of 600 kPa, at a temperature of 35°C. The selected temperature represents the MAAT of Doha plus one mean annual monthly temperature standard deviation (σ_{MAMT}); i.e. $\mathrm{MAAT} + \sigma_{\mathrm{MAMT}} = 35°\mathrm{C}$. The calibrated viscoelastic model characterising each mix is used along with the time–temperature shift factors to predict the viscoelastic strain response for the applied stress history. This is based on the given that time–temperature superposition is applicable with growing damage (Chehab, 2002; Chehab et al., 2002; Yun & Richard Kim, 2013). To compare the damage behaviour of the mixes, the C vs. S curves plotted in Figure 3 are examined, considering a drop of the normalised pseudostiffness,

Table 4. Design thickness and rehabilitation schedule based on Pavement-ME IRI predictions.

Mix	Design thickness (cm) [in]	Predicted rut depth at 20 years (cm) [in]	Year of maintenance/rehabilitation activity 🟦 Chip Seal ▨ Overlay
19M-H	**17.0 [6.75]**	**0.70 [0.28]**	
19M-W-F	17.5 [7.00]	0.85 [0.34]	
19M-W-C	17.0 [6.75]	0.75 [0.30]	
19M-W-O	17.0 [6.75]	0.65 [0.26]	
25U-H	**21.5 [8.50]**	**1.00 [0.42]**	
25U-W-F	21.5 [8.50]	1.10 [0.44]	
25U-W-C	21.5 [8.25]	0.90 [0.35]	
25U-W-O	20.0 [7.75]	0.60 [0.25]	

C, from 1 to 0.5 as a failure criterion. The corresponding cumulative damage for each mix is presented in Table 5. The change in service life is defined as the ratio of the strain achieved by WMA to that of the corresponding control HMA after 300 cycles of creep and recovery. It is assumed that HMA pavements will require major rehabilitation only at the end of their service life. The rehabilitation strategy is chosen as a 5 cm (2 in) functional polymer-modified HMA

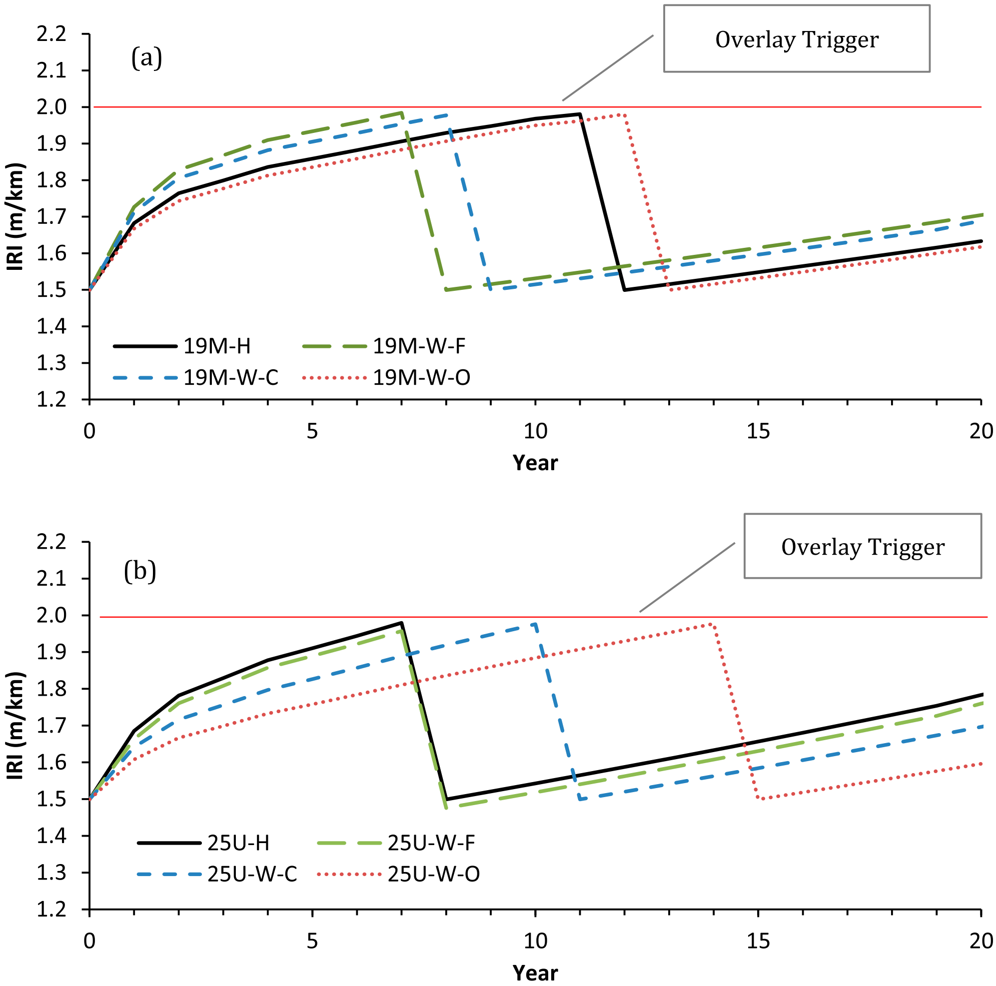


Figure 4. IRI curves with maintenance activities (HMA overlay) for HMA and WMA mixes with: (a) PG76-22 binder and 25 mm NMAS, and (b) PG64-22 binder and 19 mm NMAS.

overlay. The time of major rehabilitation for WMA pavements is calculated based on a service life of 20 years, and using the following equation:

$$\text{Year of Major Rehab} = 20\ \text{years} - (\%\text{Change in Service Life}) \times 20\ \text{years}.$$

Life-cycle assessment (LCA)

The LCA covers all life-cycle phases: materials production, construction, maintenance and rehabilitation, and operation. The end-of-life phase is excluded from the analysis because recycling is not common practice in Qatar and other GCC countries yet. The functional unit for the LCA is one lane-kilometre of the paved roadway, excluding shoulders. The analysis period is chosen as 20 years, which is the estimated design life of each pavement. The analysis period accommodates differences in the rehabilitation schedules and accounts for at least one major rehabilitation event for each mix type.

Table 5. Change in service life based on VECD.

Mix	S at $C = 0.5$	Strain* after 300 creep and recovery cycles ($\times 10^{-6}$)	Change in service life compared to HMA based on predicted strain (%)	Year of rehabilitation, assuming 20-year service life
19M-H	**15,555**	**570**	–	**20**
19M-W-F	15,450	690	– 17.4	16.5
19M-W-C	24,800	1200	– 50.4	10
10M-W-O	16,050	450	27.8	25.5
25U-H	**17,100**	**1300**	–	**20**
25U-W-F	18,500	2400	– 46.7	11
25U-W-C	19,800	980	29.8	26
25U-W-O	22,500	880	42.9	28.5

*The strain is non-LVE strain that includes long-term recoverable strains and calculated by: total cumulative strain – instantaneous recoverable strain.

The methodology follows the general recommendations of the recently released Pavement Life Cycle Assessment Framework (Harvey et al., 2016). The environmental impact of each of the mixes are acquired using PaLATE (Horvath, 2004), and based on the performance measures described and reported in the previous section. Multiple recent research studies have used PaLATE for LCA of various pavement technologies (Bloom et al., 2016; Carpenter, Gardner, Fopiano, Benson, & Edil, 2007; Cross, Chesner, Justus, & Kearney, 2011; Lee, Edil, Tinjum, & Benson, 2010; Mauro & Guerrieri, 2016). Note that currently, PaLATE does not directly accommodate WMA additives or methods; therefore, it is necessary to introduce some modifications to its environmental inventory database in order to cater for the WMA additives/mixes included in this study. Reductions in energy consumption and emissions resulting from the use of WMA technologies were acquired from SimaPro database (Goedkoop, Oele, de Schryver, Vieira, & Hegger, 2008) and incorporated in PaLATE.

The reduction values, presented in Figure 5, corresponding to the materials and mix production of asphalt mixes, reflect environmental impacts of manufacturing the warm mix additives, as well as the resulting reduction in mix production temperatures. Environmental savings for WMA mixes with unmodified binder exceed those of WMA mixes with polymer-modified binder due to higher reduction in temperature and lower dosages of WMA additives. In addition, the energy required to produce polymer-modified asphalt exceeds the savings in energy due to reduction in mixing temperature. However, reductions in GWP are achieved for all the cases considered, as seen in Figure 5. GWP indicates the global warming impacts of different gases by measuring the amount of energy (warmth) the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of carbon dioxide. A larger value of GWP indicates a more detrimental environmental impact.

Table 6 presents the assumed hauling distances used for the LCA of transport phase. Two scenarios are considered: (1) long hauling distances, and (2) short hauling distances. The long hauling scenario considered is specific for Qatar. In other regions across the world, the hauling distance is usually much shorter. The short hauling distances are assumed based on typical averages for cases in the USA.

Life-cycle cost analysis (LCCA)

NPV calculations are used to determine the life-cycle costs of the different mixes included in the scope. The NPV analysis includes material, construction, maintenance and rehabilitation phases,

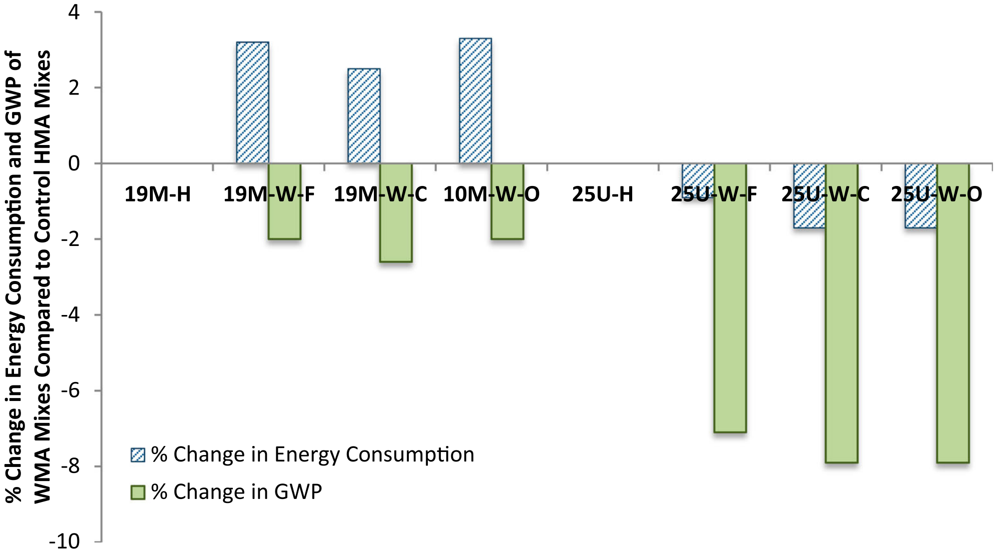


Figure 5. Per cent change in energy consumption and GWP of WMA mixes compared to control HMA mixes for the material and mix production of asphalt mixes.

Table 6. Assumed hauling distances for the LCA of transport phase.

	Distance (miles)	
Material type	Long distances*	Short distances
Crushed aggregate from quarry to plant	600	40
Polymer-modified binder (PG 76-10 V) – From supplier to plant	25	25
Straight binder (PG 64-22) – from supplier to plant	300	40
Asphalt mix – from plant to field	25	25

*Typical distances for Doha.

in addition to user costs. The material and construction prices are acquired from typical market prices in the GCC. Material shipping costs are also considered. The values used do not include overheads and profit margins.

User costs considered are defined as costs incurred by passengers due to vehicle operating costs, traffic delay (travel time costs), and crash costs associated with paving works during both initial construction and maintenance phases. Considering user costs when studying WMA mixes is important because one of the benefits of WMA compared to HMA is the reduced production and compaction temperatures. This reduction in temperature allows the freshly paved asphalt to cool at a faster rate than HMA (Kassem et al., 2015), allowing opening the road to traffic in a shorter period of time. In this study, only traffic delay costs are considered because they are the most relevant.

To calculate the NPV, an internal rate of return of 4% is used. The maintenance and rehabilitation schedules are acquired based on the three performance measures described in the previous sections. The user costs are calculated based on the following assumptions from a complementary study conducted by the authors (Kassem, Chehab, & Saad, 2014):

- a truck traffic volume of 15,000 AADTT comprises of 50% (7500) single trucks and 50% (7500) combination trucks, and a passenger vehicle volume of 50,000 vehicles;

- equal hourly distribution of traffic;
- a value of user's time of 21 USD for passenger cars, 34 USD for single-unit trucks, and 41 USD for combination trucks. A finite-element model (FEM) developed by (Kassem et al., 2015) to predict the cooling time of asphalt pavements is used to determine the cooling time for each of the mixes included in the scope. Based on the FEM tool, an average time saving of 2 h and 45 min is considered for all cases associated with WMA mixes (Kassem et al., 2015).

Results and analysis

Results of performance assessment

Based on the results of the material characterisation and the extracted performance measures, the following general conclusions can be drawn:

- the effect of WMA additives on the mechanical properties of asphalt mixes in compression state, associated with the susceptibility to rutting, is dependent on the type of binder used;
- when compared to control HMA mixes, the organic WMA additive improves resistance to rutting when used with both modified and unmodified binders;
- the chemical additive is able to improve the resistance to rutting as compared to its control HMA when added to mixes with unmodified binder but it is not the case when used in mixes with modified binder;
- for mixes with modified binder, WMA mixes with the foaming-based additive exhibit similar performance to those of HMA. Additionally, for unmodified binder mixes, the foaming-based additive helps significantly reduce the WMA mix's resistance to rutting;
- results of the Pavement-ME runs show that fatigue resistance of WMA mixes is similar to that of the control HMA for both binder types. A similar finding was reached by (Sadeq, Al-Khalid, Masad, & Sirin, 2016). It is worth noting, however, that the predicted fatigue cracking values are small compared to typical failure criteria due to the thick pavement section as well as the hot climatic conditions.

Results of LCA

The changes in energy consumption and GWP for the WMA mixes as compared to that for control HMA mixes, based on three different performance measures, are presented in Figure 6 and Figure 7 respectively. The following conclusions can be drawn:

- *Effect of Asphalt Binder Type*:
  - for the mixes included in the scope, in general, greater environmental benefits are reaped when WMA is used with unmodified binder, likely due to the lower dosages of WMA additives and higher reductions in temperature achieved compared to the WMA mixes with modified binder. In addition, environmental impacts associated with the polymer modifier may offset the environmental benefits of WMA mixes with modified binder.
- *Effect of Performance Measure*:
  - the LCA results reflect the outcomes of the material characterisation and the extracted performance measures. For example, 19M-W-C and 25U-W-F have low stiffness and a relatively high susceptibility to damage; therefore, their environmental impact is higher than other comparable mixes due to more frequent need for rehabilitation;

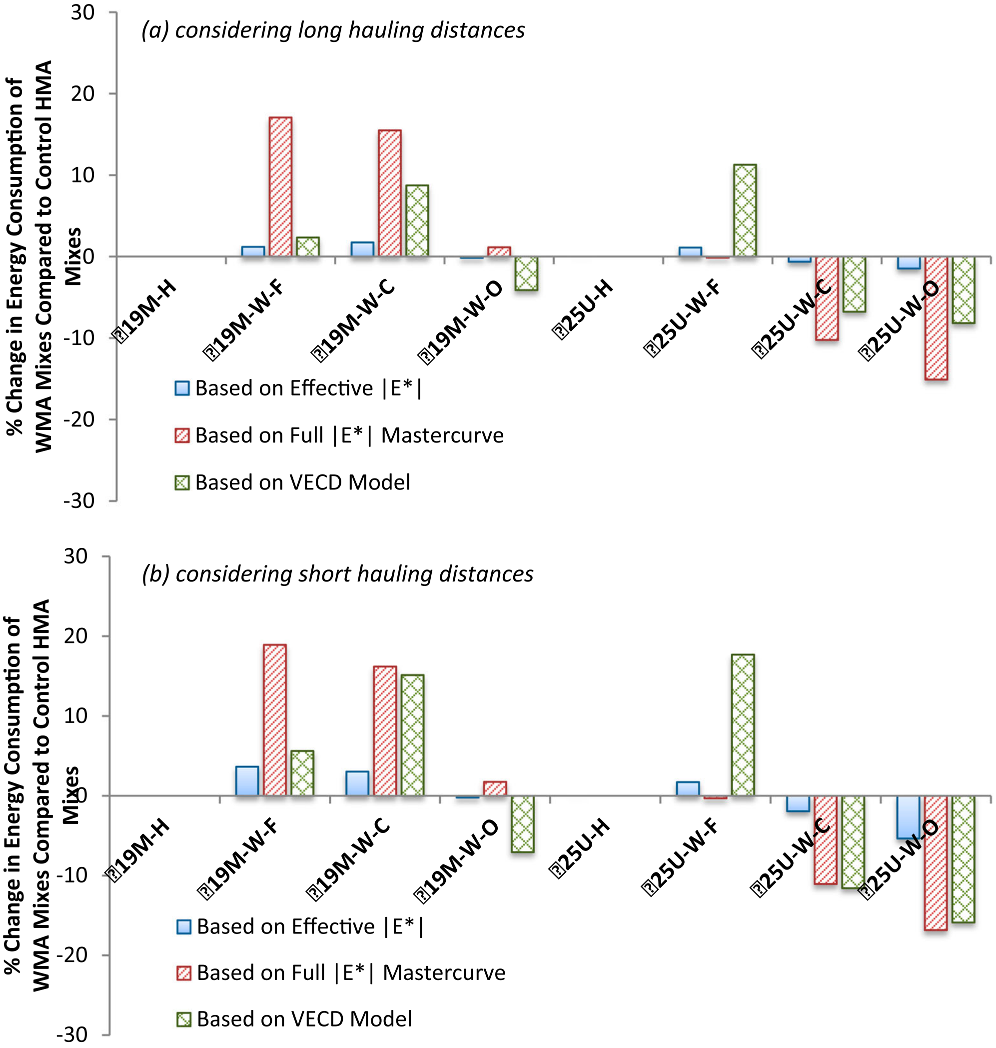


Figure 6. Changes in energy consumption for the WMA mixes included in the scope compared to control HMA mixes, based on three different performance measures, considering: (a) long hauling distances, and (b) short hauling distances.

  - the performance measure used to acquire the change in service life or estimate the maintenance and rehabilitation schedule has a significant impact on the outcome of the LCA. For example, 19M-W-O seems more favourable than HMA when relying on Pavement-ME results; whereas, it shows unfavourable environmental impacts when relying on LVE and VECD results;
  - in general, when the performance indicator is acquired using Pavement-ME, the magnitude of the change in energy consumption and GWP is smaller compared to when the performance indicator is acquired using LVE or VECD. This is likely because Pavement-ME considers a much wider array of input parameters beyond asphalt material properties.
- *Effect of Hauling Distance*:

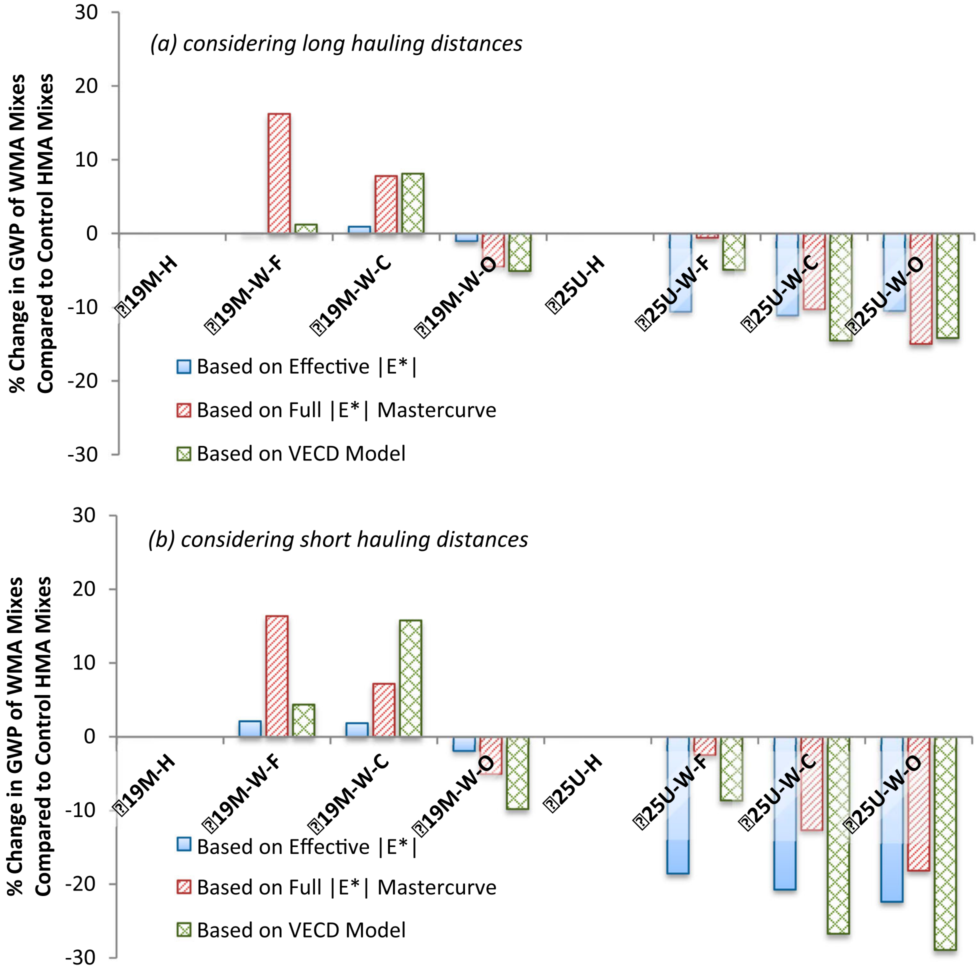


Figure 7. Changes in GWP for the WMA mixes included in the scope compared to control HMA mixes, based on three different performance measures, considering: (a) long hauling distances, and (b) short hauling distances.

  ○ longer hauling distances (transport phase) tend to mask, to a certain extent, the environmental benefits or lack thereof of WMA mixes, with greater effect on GWP. Comparing Figure 8 and Figure 9 further validates the significant effect of the transport phase on the life-cycle environmental impacts of an asphalt pavement.

Figure 8 and Figure 9 show the energy consumption and GWP by life-cycle phase for each mix, considering long hauling distances and short hauling distances, respectively. These figures serve as justification for the conclusions drawn above. Comparing Figure 8 and Figure 9 lead to the following inferences:

- the asphalt material production phase, in general, results in a considerable portion of the life-cycle environmental impacts of asphalt pavements. As a result, reductions in energy consumption and emissions in the production phase of WMA mixes can potentially be appreciable when considering the entire life cycle of a pavement;

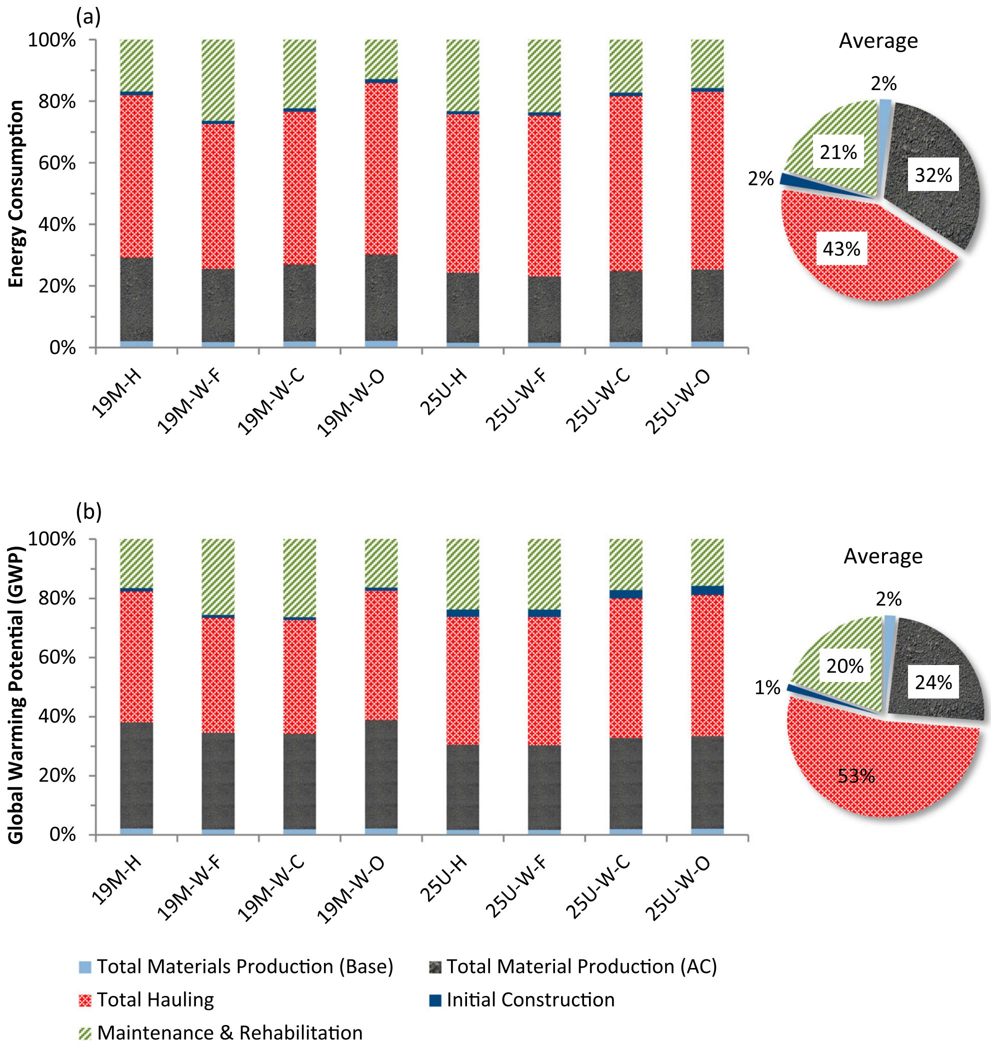


Figure 8. (a) Energy consumption and (b) GWP by life-cycle phase considering long hauling distances.

- initial construction constitutes a negligible portion of the life-cycle environmental impacts of a pavement;
- the maintenance and rehabilitation phase(s) is a major contributor to the life-cycle environmental impacts of a pavement. Therefore, it is essential to consider the performance of asphalt mixes, and the resulting maintenance/rehabilitation schedules and/or changes in service life when conducting life-cycle analysis;
- as previously stated, the transport phase has a significant effect on the life-cycle environmental impacts of an asphalt pavement, with a greater effect on GWP. Longer hauling distances, therefore, can mask the environmental benefits reaped in other stages.

In general, the LCA findings are in line with previous research findings that showed that, in general, the material production stage contributes most to GWP of asphalt mixtures (Wu & Qian, 2014). Asphalt mix production and maintenance stages are also critical to the life-cycle

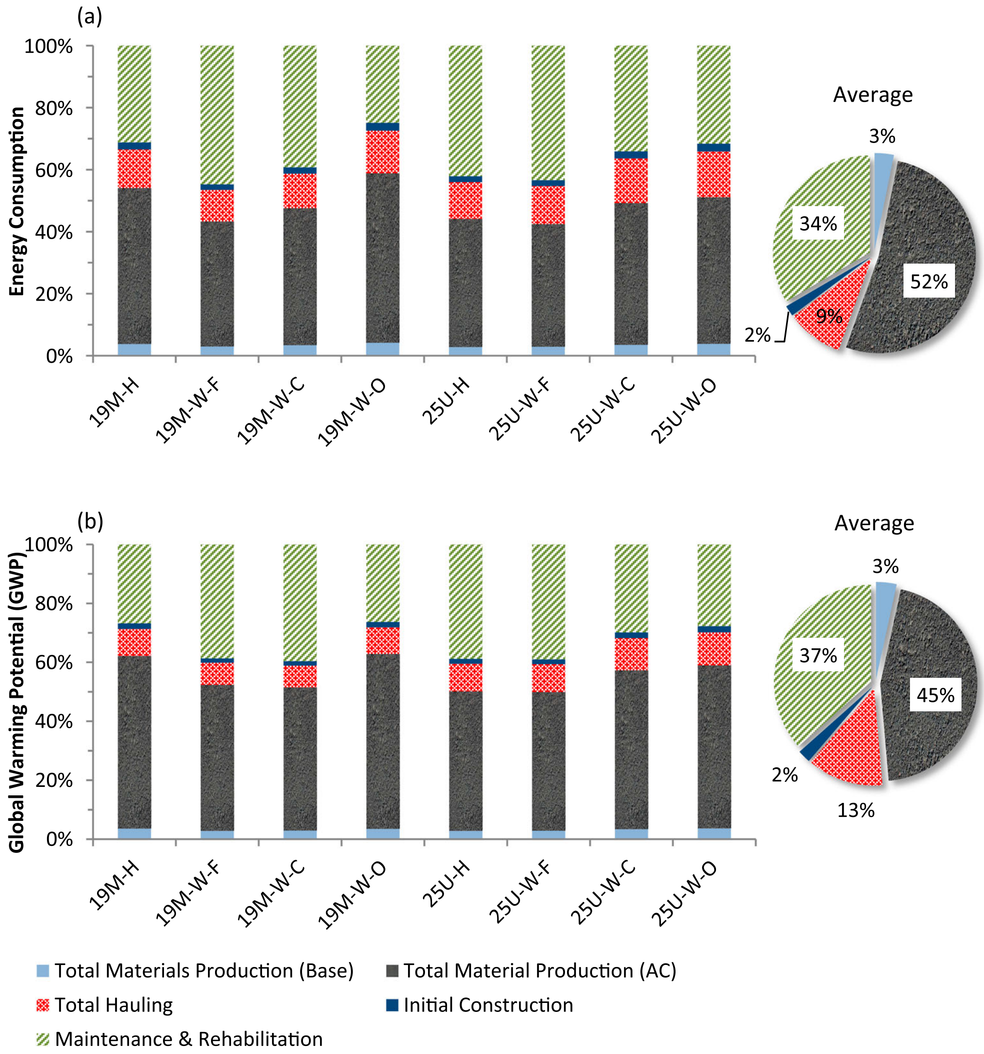
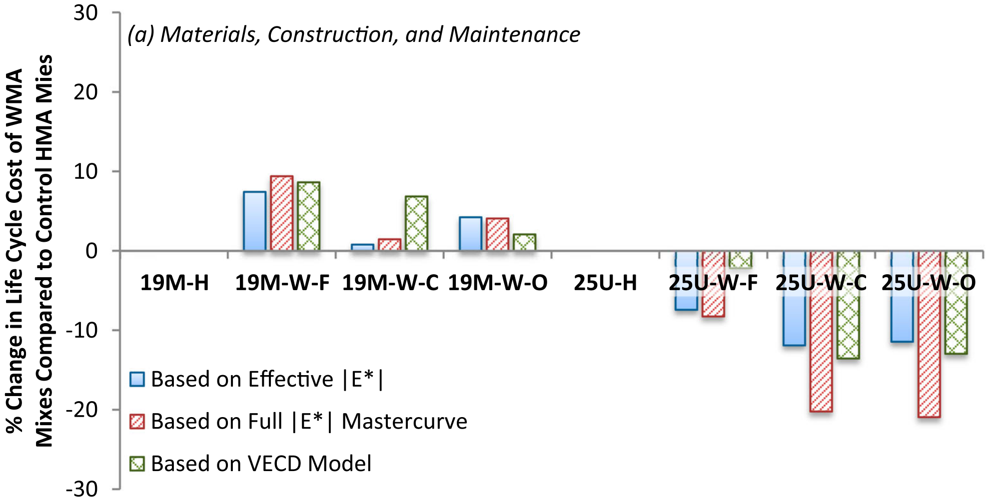


Figure 9. (a) Energy consumption and (b) GWP by life-cycle phase considering short hauling distances.

environmental impacts of asphalt pavements; whereas, construction and end of life stages make up little portion of the burden (Wu & Qian, 2014). It has also been reported that transportation and construction phases contribute most to GWP; whereas, asphalt materials and mix production stages contribute most to energy consumption (fossil fuel depletion) (Hassan, 2010). In previously conducted studies, WMA pavements experienced more environmental impacts during the materials production stage than HMA pavements, mainly due to the production of warm mix agents (Wu & Qian, 2014). These differences, however, were offset in the asphalt mix production stage due to the lowered mixing temperatures (Wu & Qian, 2014).

Results of LCCA

The changes in life-cycle costs for the WMA mixes compared to control HMA mixes, based on three different performance measures are presented in Figure 10. Figure 10(a) shows the costs for



(b) Materials, Construction, Maintenance, and User Costs

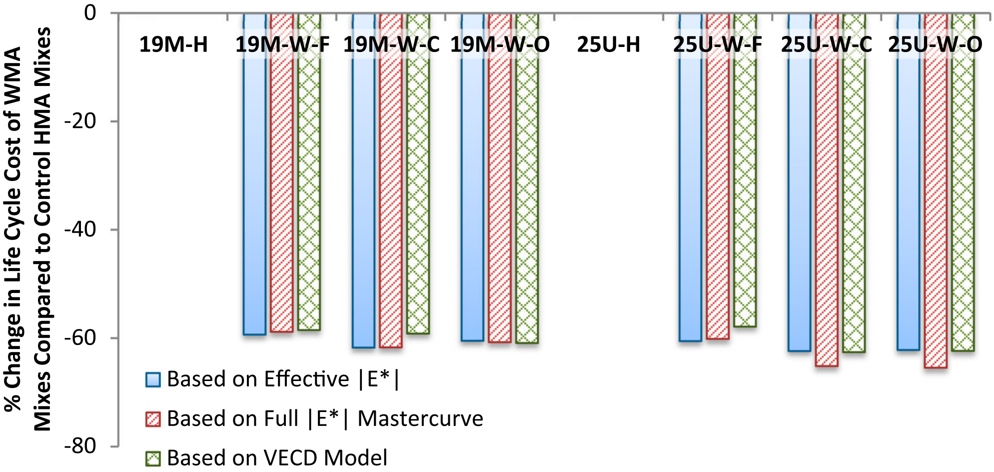


Figure 10. Changes in life-cycle costs for the WMA mixes included in the scope compared to control HMA mixes for (a) materials, construction and maintenance phases, (b) materials, construction and maintenance phases, and user costs.

materials, construction and maintenance phases, while Figure 10(b) shows the costs materials, construction and maintenance phases, in addition to user costs. It is important to keep in mind that the LCCA considers materials and construction prices in Qatar, and results are therefore contextual. The following can be deduced for the given context:

- in general, greater economic benefits are reaped when WMA technologies are used with unmodified binder, especially for chemical and organic technologies. Using WMA technologies with modified binder, on the other hand, may lead to marginally higher economic costs due to the added cost of the polymer modifier;
- changes in cost in the materials, construction and maintenance phases for the WMA mixes compared to control HMA mixes are more pronounced when using performance measures based on Pavement-ME;

- a main economic advantage of WMA mixes is the reduction in user costs due to savings in time to open to traffic. Reduced user costs can be a motivating factor for adopting WMA technologies, especially in urban areas and for roadways where traffic volume is high. In addition, incorporating user costs in the LCCA masks the effect of materials, construction, and maintenance.

Conclusions, limitations, and recommendations

This paper presents a general framework for assessing the sustainability of different types of asphalt materials and technologies. The framework includes performance assessment, LCA, and LCCA, and is applied to the case of WMA. The performance assessment is based on two different material characterisation methods: (1) LVE response functions, (2) VECD material model. Three performance measures are extracted from these two material characterisation methods to be used in the LCA and LCCA. The following conclusions are drawn from the study:

- the outcomes of the LCA and LCCA are affected by the performance measure used to predict the maintenance schedule or change in service life. Choosing a performance measure should depend on the objective of the LCA and LCCA, and the time and resources available to characterise the performance of the mix or analyse the performance of the pavement structure;
- in general, under the conditions examined in the study, WMA mixes showed more favourable environmental and economic results compared to control HMA mixes when used with unmodified binder;
- if the transportation distance is large, savings in energy and carbon footprint during the material production phase can be offset by the impacts of the transport phase;
- a main economic advantage of WMA mixes is the reduction in user costs due to savings in time to open to traffic.

The limitations and corresponding recommendations of this study are summarised below:

- life-cycle inventory data sources used in this study are specific to the USA or Europe. Moreover, performance prediction functions used in this study were calibrated for the USA. Although the results offer a general idea about the different mixes included in the scope, they are not conclusive for any geographic location. Region-specific environmental impact data is needed to make solid conclusions for specific scenarios, especially in countries outside the USA;
- there exists an inherent uncertainty in LCA analyses due to the variability in inputs and the variability in the life-cycle inventory data acquired from different sources. Some studies have began examining parts of this variability (Tatari, Nazzal, & Kucukvar, 2012). More research is required in order to find a way to practically incorporate uncertainty analysis in LCA;
- the results of this study may be impacted by the maintenance triggers and corresponding assumptions;
- this paper presents the results of LCA and LCCA separately. A combined economic-environmental indicator may be developed in the future in order to come up with a single figure to simplify the decision-making process;
- validation across real performance data is not addressed in the scope but is an essential topic for future research.

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Disclosure statement

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